Section Five

Courses

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

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

At the end of the seventh week of each term, a list of courses to be offered the following term is published by the Registrar's Office. On the day of registration (see Academic Calendar), an updated and revised course schedule is published announcing the courses, class hours, and room assignments for the term. Students may not schedule two courses taught at the same time.

Abbreviations

Ae	Aerospace
An	Anthropology
ACM	Applied and Computational Mathematics
AM	Applied Mechanics
APh	Applied Physics
Art	Art History
Ay	Astrophysics
BMB	Biochemistry and Molecular Biophysics
BE	Bioengineering
Bi	Biology
BEM	Business Economics and Management
ChE	Chemical Engineering
Ch	Chemistry
CE	Civil Engineering
CNS	Computation and Neural Systems
CS	Computer Science
CDS	Control and Dynamical Systems
Ec	Economics
EE	Electrical Engineering
EST	Energy Science and Technology
E	Engineering
En	English
ESL	English As a Second Language
ESE	Environmental Science and Engineering
F	Film
Ge	Geological and Planetary Sciences
H	History
HPS	History and Philosophy of Science
Hum	Humanities
ISP	Independent Studies Program
IST	Information Science and Technology
L	Languages
Law	Law
MS	Materials Science
Ma	Mathematics
ME	Mechanical Engineering
Mu	Music
PA	Performance and Activities
Pl	Philosophy
PE	Physical Education
Ph	Physics
PS	Political Science
Psy	Psychology
SS	Social Science

Ae 100. Research in Aerospace. *Units to be arranged in accordance with work accomplished.* Open to suitably qualified undergraduates and first-year graduate students under the direction of the staff. Credit is based on the satisfactory completion of a substantive research report, which must be approved by the Ae 100 adviser and by the option representative.

Ae/APh/CE/ME 101 abc. Fluid Mechanics. *9 units (3-0-6); first, second, third terms. Prerequisites: APh 17 or ME 18, and ME 19 or equivalent, ACM 95/100 or equivalent (may be taken concurrently).* Fundamentals of fluid mechanics. Microscopic and macroscopic properties of liquids and gases; the continuum hypothesis; review of thermodynamics; general equations of motion; kinematics; stresses; constitutive relations; vorticity, circulation; Bernoulli's equation; potential flow; thin-airfoil theory; surface gravity waves; buoyancy-driven flows; rotating flows; viscous creeping flow; viscous boundary layers; introduction to stability and turbulence; quasi one-dimensional compressible flow; shock waves; unsteady compressible flow; acoustics. Instructors: Gharib, Pullin.

Ae/AM/CE/ME 102 abc. Mechanics of Structures and Solids. *9 units (3-0-6); first, second, third terms. Prerequisite: ME 35 abc or equivalent.* Static and dynamic stress analysis. Two- and three-dimensional theory of stressed elastic solids. Analysis of structural elements with applications in a variety of fields. Variational theorems and approximate solutions, finite elements. A variety of special topics will be discussed in the third term such as, but not limited to, elastic stability, wave propagation, and introductory fracture mechanics. Instructors: Bhattacharya, Ravichandran.

Ae/APh 104 abc. Experimental Methods. *9 units (3-0-6) first term; (1-3-5) second, third terms. Prerequisites: ACM 95/100 abc or equivalent (may be taken concurrently), Ae/APh/CE/ME 101 abc or equivalent (may be taken concurrently).* Lectures on experiment design and implementation. Measurement methods, transducer fundamentals, instrumentation, optical systems, signal processing, noise theory, analog and digital electronic fundamentals, with data acquisition and processing systems. Experiments (second and third terms) in solid and fluid mechanics with emphasis on current research methods. Instructor: McKeon.

Ae 105 abc. Aerospace Engineering. *9 units (3-0-6); first, second, third terms. Prerequisites: APh 17 or ME 18 and ME 19 or equivalent.* Part a: Introduction to spacecraft systems and subsystems, mission design, fundamentals of orbital and rocket mechanics, launch vehicles and space environments; JPL-assisted design exercise; spacecraft mechanical, structural, and thermal design; numerical modeling, test validation. Part b: Introduction to guidance, navigation, and control (GNC), measurement systems, Kalman filtering, system analysis, simulation, statistical error analysis, case studies of JPL GNC applications; preliminary discussion and setup for team project leading to system requirements review. Part c: Team project leading to preliminary design review and critical design review. Instructors: Pellegrino, Davis, Kim, Watkins.

CE/Ae/AM 108 abc. Computational Mechanics. *9 units (3-0-6).* For course description, see Civil Engineering.

Ae 115 ab. Spacecraft Navigation. *9 units (3-0-6); first, second terms. Prerequisite: CDS 110 a.* This course will survey all aspects of modern spacecraft navigation, including astrodynamics, tracking systems for both low-Earth and deep-space applications (including the Global Positioning System and the Deep Space Network observables), and the statistical orbit determination problem (in both the batch and sequential Kalman filter implementations). The course will describe some of the scientific applications directly derived from precision orbital knowledge, such as planetary gravity field and topography modeling. Numerous examples drawn from actual missions as navigated at JPL will be discussed. Not offered 2010–11.

Ae/ME 120 ab. Combustion Fundamentals. *9 units (3-0-6); second, third terms. Prerequisite: ME 119 a or equivalent.* The course will cover thermodynamics of pure substances and mixtures, equations of state, chemical equilibrium, chemical kinetics, combustion chemistry, transport phenomena, and the governing equations for multicomponent gas mixtures. Topics will be chosen from non-premixed and premixed flames, the fluid mechanics of laminar flames, flame mechanisms of combustion-generated pollutants, and numerical simulations of multicomponent reacting flows. Instructor: Blanquart.

Ae 121 abc. Space Propulsion. *9 units (3-0-6); each term. Open to all graduate students and to seniors with instructor's permission.* Modern aspects of rocket, electrical, and nuclear propulsion systems and the principles of their application to lifting, ballistic, and spaceflight trajectories. Combustion and burning characteristics of solid and liquid propellants, liquid-propellant fuel systems, and combustion instability. Fundamentals of electric propulsion including ion thrusters, MHD, Hall effect, and arcjets. Introduction to spacecraft station-keeping, stability, and control. Instructor: Polk.

Ae 150 abc. Aerospace Engineering Seminar. *1 unit; first, second, third terms.* Speakers from campus and outside research and manufacturing organizations discuss current problems and advances in aerospace engineering. Graded pass/fail. Instructor: Meiron.

EE/Ae 157 ab. Introduction to the Physics of Remote Sensing. *9 units (3-0-6).* For course description, see Electrical Engineering.

Ae 159. Space Optical System Engineering. *9 units (3-0-6); third term. Prerequisites: Ph 2, EE/Ae 157, or equivalent; APh 23 desirable.* Introduction to optical system engineering for remote sensing from space will be presented. End-to-end optical systems are discussed within the framework of the 10 scientific/technical disciplines required to build a successful system: optical engineering, physical optics of materials, solid-state physics/detectors, mechanics and mechanisms engineering, wavefront sensing and control, structures and dynamics, thermal engineering, spacecraft engineering, psychology of vision and software processing of images, and end-to-end system validation and calibration. Emphasis will be on the development of optical engineering tools. Not offered 2010–11.

Ae/Ge/ME 160 ab. Continuum Mechanics of Fluids and Solids. *9 units (3-0-6); first, second terms.* Elements of Cartesian tensors. Configurations and motions of a body. Kinematics—study of deformations, rotations and stretches, polar decomposition. Lagrangian and Eulerian strain velocity and spin tensor fields. Irrotational motions, rigid motions. Kinetics—balance laws. Linear and angular momentum, force, traction stress. Cauchy's theorem, properties of Cauchy's stress. Equations of motion, equilibrium equations. Power theorem, nominal (Piola-Kirchoff) stress. Thermodynamics of bodies. Internal energy, heat flux, heat supply. Laws of thermodynamics, notions of entropy, absolute temperature. Entropy inequality (Clausius-Duhem). Examples of special classes of constitutive laws for materials without memory. Objective rates, corotational, convected rates. Principles of materials frame indifference. Examples: the isotropic Navier-Stokes fluid, the isotropic thermoelastic solid. Basics of finite differences, finite elements, and boundary integral methods, and their applications to continuum mechanics problems illustrating a variety of classes of constitutive laws. Instructor: Ortiz.

Ae/CE 165 ab. Mechanics of Composite Materials and Structures. *9 units (2-2-5); second, third terms. Prerequisite: Ae/AM/CE/ME 102 a or ME 65.* Introduction and fabrication technology, elastic deformation of composites, stiffness bounds, on- and off-axis elastic constants for a lamina, elastic deformation of multidirectional laminates (lamination theory, ABD matrix), effective hygrothermal properties, mechanisms of yield and failure for a laminate, strength of a single ply, failure models, splitting and delamination. Experimental methods for characterization and testing of composite materials. Design criteria, application of design methods to select a suitable laminate using composite design software, hand layup of a simple laminate and measurement of its stiffness and thermoelastic coefficients. Not offered 2010–11.

Ae 200. Advanced Research in Aerospace. *Units to be arranged.* Ae.E. or Ph.D. thesis level research under the direction of the staff. A written research report must be submitted during finals week each term.

Ae 201. Advanced Fluid Mechanics. *9 units (3-0-6); second term. Prerequisites: Ae/APh/CE/ME 101 abc or equivalent; AM 125 abc or ACM 101 abc (may be taken concurrently).* Foundations of the mechanics of real fluids. Basic concepts will be emphasized. Subjects covered will include a selection from the following topics: physical properties of real gases; the equations of motion of viscous and inviscid fluids; the dynamical significance of vorticity; vortex dynamics; exact solutions; motion at high Reynolds numbers; hydrodynamic stability; boundary layers; flow past bodies; compressible flow; subsonic, transonic, and supersonic flow; shock waves. Not offered 2010–11.

Ae 204 ab. Technical Fluid Mechanics. *9 units (3-0-6); second, third terms. Prerequisite: Ae/APh/CE/ME 101 abc or equivalent.* External and internal flow problems encountered in engineering, for which only empirical methods exist. Turbulent shear flow, separation, transition, three-dimensional and nonsteady effects. Basis of engineering practice in the design of devices such as mixers, ejectors, diffusers, and control valves. Studies of flow-induced oscillations, wind effects on structures, vehicle aerodynamics. Not offered 2010–11.

Ae 208 abc. GALCIT Colloquium. *1 unit; first, second, third terms.* A seminar course in fluid, solid, space, and bio mechanics. Weekly lectures on current developments are presented by staff members, graduate students, and visiting scientists and engineers. Graded pass/fail. Instructors: Pellegrino, McKeon.

Note: The following courses, with numbers greater than 209, are one-, two-, or three-term courses offered to interested students. Depending on conditions, some of the courses may be taught as tutorials or reading courses, while others may be conducted more formally.

Ae/AM/MS/ME 213. Mechanics and Materials Aspects of Fracture. *9 units (3-0-6); second term. Prerequisites: Ae/AM/CE/ME 102 abc (concurrently) or equivalent and instructor's permission.* Analytical and experimental techniques in the study of fracture in metallic and non-metallic solids. Mechanics of brittle and ductile fracture; connections between the continuum descriptions of fracture and micromechanisms. Discussion of elastic-plastic fracture analysis and fracture criteria. Special topics include fracture by cleavage, void growth, rate sensitivity, crack deflection and toughening mechanisms, as well as fracture of nontraditional materials. Fatigue crack growth and life prediction techniques will also be discussed. In addition, "dynamic" stress wave dominated, failure initiation growth and arrest phenomena will be covered. This will include traditional dynamic fracture considerations as well as discussions of failure by adiabatic shear localization. Not offered 2010–11.

Ae/AM/CE/ME 214 abc. Computational Solid Mechanics. *9 units (3-0-6); first, second, third terms. Prerequisites: AM 125 abc or equivalent; ACM 100 abc or equivalent; CE/AM/Ae 108 abc or equivalent or instructor's permission; Ae/AM/CE/ME 102 abc or equivalent; Ae/Ge/ME 160 ab desirable or taken concurrently.* Introduction to the use of numerical methods in the solution of solid mechanics and materials problems. First term: geometrical representation of solids. Automatic meshing. Approximation theory. Interpolation error estimation. Optimal and adaptive meshing. Second term: variational principles in linear elasticity. Finite element analysis. Error estimation. Convergence. Singularities. Adaptive strategies. Constrained problems. Mixed methods. Stability and convergence. Variational problems in nonlinear elasticity. Consistent linearization. The Newton-Rahpson method. Bifurcation analysis. Adaptive strategies in nonlinear elasticity. Constrained finite deformation problems. Contact and friction. Third term: time integration. Algorithm analysis. Accuracy, stability, and convergence. Operator splitting and product formulas. Coupled problems. Impact and friction. Subcycling. Space-time methods. Inelastic solids. Constitutive updates. Stability and convergence. Consistent linearization. Applications to finite deformation viscoplasticity, viscoelasticity, and Lagrangian modeling of fluid flows. Not offered 2010–11.

Ae/AM/ME 215. Dynamic Behavior of Materials. *9 units (3-0-6); first term. Prerequisites: ACM 100 abc or AM 125 abc; Ae/AM/CE/ME 102 abc.* Fundamentals of theory of wave propagation; plane waves, wave guides, dispersion relations; dynamic plasticity, adiabatic shear banding; dynamic fracture; shock waves, equation of state. Not offered 2010–11.

Ae 220. Theory of Structures. *9 units (3-0-6); first term. Prerequisite: Ae/AM/CE/ME 102 abc.* Fundamentals of buckling and stability, total potential energy and direct equilibrium approaches; classification of instabilities into snap-through type and bifurcation type; rigid-elastic structures, eigenvalues, and eigenvectors of stiffness matrix; elastic structures; approximate estimates of buckling load; Rayleigh quotient; lateral buckling of columns: Euler strut, imperfections, Southwell plot, beam-columns, stability coefficients, buckling of frames; elasto-plastic buckling: tangent-modulus, double-modulus, Shanley's analysis; lateral-torsional buckling of beams; buckling of plates; buckling of cylindrical shells. Instructor: Pellegrino.

Ae/CE 221. Space Structures. *9 units (3-0-6); second term.* This course examines the links between form, geometric shape, and structural performance. It deals with different ways of breaking up a continuum, and how this affects global structural properties; structural concepts and preliminary design methods that are used in tension structures and deployable structures. Geometric foundations, polyhedra and tessellations, surfaces; space frames, examples of space frames, stiffness and structural efficiency of frames with different repeating units; sandwich plates; cable and membrane structures, form-finding, wrinkle-free pneumatic domes, balloons, tension-stabilized struts, tensegrity domes; deployable and adaptive structures, coiled rods and their applications, flexible shells, membranes, structural mechanisms, actuators, concepts for adaptive trusses and manipulators. Instructor: Pellegrino.

Ae/AM/ME 223. Plasticity. *9 units (3-0-6); second term. Prerequisite: Ae/AM/CE/ME 102 abc or instructor's permission.* Theory of dislocations in crystalline media. Characteristics of dislocations and their influence on the mechanical behavior in various crystal structures. Application of dislocation theory to single and polycrystal plasticity. Theory of the inelastic behavior of materials with negligible time effects. Experimental background for metals and fundamental postulates for plastic stress-strain relations. Variational principles for incremental elastic-plastic problems, uniqueness. Upper and lower bound theorems of limit analysis and shakedown. Slip line theory and applications. Additional topics may include soils, creep and rate-sensitive effects in metals, the thermodynamics of plastic deformation, and experimental methods in plasticity. Instructor: Shukla.

Ae/AM/ME 225. Special Topics in Solid Mechanics. *Units to be arranged.* Subject matter will change from term to term depending upon staff and student interest but may include such topics as structural dynamics; aeroelasticity; thermal stress; mechanics of inelastic and composite materials; and nonlinear problems. Not offered 2010–11.

Ae 228. Computational Mechanics Simulations Using Particles. *9 units (3-0-6); first term. Prerequisites: Ae/AM/CE/ME 214 or equivalent or Ae/ACM/ME 232 or equivalent, ACM 104, ACM 105, or equivalent.* Particle simulations of continuum and discrete systems. Advances in molecular, mesoscopic, and macroscale simulations using particles, identification of common computing paradigms and challenges across disciplines, discretizations and representations using particles, fast summation algorithms, time integrators, constraints, and multiresolution. Exercises will draw on problems simulated using particles from diverse areas such as fluid and solid mechanics, computer graphics, and nanotechnology. Not offered 2010–11.

Ae/ACM/ME 232 abc. Computational Fluid Dynamics. *9 units (3-0-6); first, second, third terms. Prerequisites: Ae/APh/CE/ME 101 abc or equivalent; ACM 100 abc or equivalent.* Development and analysis of algorithms used in the solution of fluid mechanics problems. Numerical analysis of discretization schemes for partial differential equations including interpolation, integration, spatial discretization, systems of ordinary differential equations; stability, accuracy, aliasing, Gibbs and Runge phenomena, numerical dissipation and dispersion; boundary conditions. Survey of finite difference, finite element, finite volume and spectral approximations for the numerical solution of the incompressible and compressible Euler and Navier-Stokes equations, including shock-capturing methods. Instructor: Meiron.

Ae 233. Hydrodynamic Stability. *9 units (3-0-6); third term. Prerequisite: Ae/APh/CE/ME 101 abc or equivalent.* Laminar-stability theory as a guide to laminar-turbulent transition. Rayleigh equation, instability criteria, and response to small inviscid disturbances. Discussion of Kelvin-Helmholtz, Rayleigh-Taylor, Richtmyer-Meshkov, and other instabilities, for example, in geophysical flows. The Orr-Sommerfeld equation, the dual role of viscosity, and boundary-layer stability. Modern concepts such as pseudomomentum conservation laws and nonlinear stability theorems for 2-D and geophysical flows. Weakly nonlinear stability theory and phenomenological theories of turbulence. Not offered 2010–11.

Ae 234. Hypersonic Aerodynamics. *9 units (3-0-6); first term. Prerequisites: Ae/APh/CE/ME 101 abc or equivalent, AM 125 abc, or instructor's permission.* An advanced course dealing with aerodynamic problems of flight at hypersonic speeds. Topics are selected from hypersonic small-disturbance theory, blunt-body theory, boundary layers and shock waves in real gases, heat and mass transfer, testing facilities and experiment. Not offered 2010–11.

Ae 235. Rarefied Gasdynamics. *9 units (3-0-6); third term.* Molecular description of matter; distribution functions; discrete-velocity gases. Kinetic theory: free-path theory, internal degrees of freedom. Boltzmann equation: BBGKY hierarchy and closure, H theorem, Euler equations, Chapman-Enskog procedure, free-molecule flows. Collisionless and transitional flows. Direct simulation Monte Carlo methods. Applications. Not offered 2010–11.

Ae 237 ab. Nonsteady Gasdynamics. *9 units (3-0-6); first, second terms.* Part a: dynamics of shock waves, expansion waves, and related discontinuities in gases. Adiabatic phase-transformation waves. Interaction of waves in one- and two-dimensional flows. Boundary layers and shock structure. Applications and shock tube techniques. Part b: shock and detonation waves in solids and liquids. Equations of state for hydrodynamic computations in solids, liquids, and explosive reaction products. CJ and ZND models of detonation in solids and liquids. Propagation of shock waves and initiation of reaction in explosives. Interactions of detonation waves with water and metals. Not offered 2010–11.

Ae 239 ab. Turbulence. *9 units (3-0-6); first, second terms. Prerequisites: Ae/APh/CE/ME 101 abc; AM 125 abc or ACM 101 abc.* Reynolds-averaged equations and the problem of closure. Statistical description of turbulence. Homogeneous isotropic turbulence and structure of fine scales. Turbulent shear flows. Physical and spectral models. Subgrid-scale modeling. Turbulent mixing. Structure of low and high Reynolds number wall turbulence. Not offered 2010–11.

Ae 240. Special Topics in Fluid Mechanics. *Units to be arranged; first term.* Subject matter changes depending upon staff and student interest. Not offered 2010–11.

Ae 241. Special Topics in Experimental Fluid and Solid Mechanics. *9 units (3-0-6); second term. Prerequisite: Ae/APh 104 or equivalent or instructor's permission.* Energy from wind and sea. Not offered 2010–11.

Ae/BE 242. Biological Flows: Propulsion. *9 units (3-0-6); second term. Prerequisite: Ae/APh/CE/ME 101 abc or equivalent or ChE 103 a.* Physical principles of unsteady fluid momentum transport: equations of motion, dimensional analysis, conservation laws. Unsteady vortex dynamics: vorticity generation and dynamics, vortex dipoles/rings, wake structure in unsteady flows. Life in moving fluids: unsteady drag, added-mass effects, virtual buoyancy, bounding and schooling, wake capture. Thrust generation by flapping, undulating, rowing, jetting.

Low Reynolds number propulsion. Bioinspired design of propulsion devices. Instructor: Dabiri.

BE/Ae 243. Biological Flows: Transport and Circulatory Systems. *9 units (3-0-6).* For course description, see Bioengineering.

Ae 244. Mechanics of Nanomaterials. *9 units (3-0-6); third term.* Basics of the mechanics of nanomaterials, including the physical and chemical synthesis/processing techniques for creating nanostructures and their relation with mechanical and other structural properties. Overview of the properties of various types of nanomaterials including nanostructured metals/ceramics/composites, nanowires, carbon nanotubes, quantum dots, nanopatterns, self-assembled colloidal crystals, magnetic nanomaterials, and biorelated nanomaterials. Innovative experimental methods and microstructural characterization developed for studying the mechanics at the nanoscale will be described. Recent advances in the application of nanomaterials in engineering systems and patent-related aspects of nanomaterials will also be covered. Open to undergraduates with instructor's permission. Instructor: Daraio.

Ae/Ge/ME 266 ab. Dynamic Fracture and Frictional Faulting. *9 units (3-0-6); second, third terms. Prerequisite: Ae/AM/CE/ME 102 abc or Ae/Ge/ME 160 ab or instructor's permission.* Introduction to elastodynamics and waves in solids. Dynamic fracture theory, energy concepts, cohesive zone models. Friction laws, nucleation of frictional instabilities, dynamic rupture of frictional interfaces. Radiation from moving cracks. Thermal effects during dynamic fracture and faulting. Crack branching and faulting along nonplanar interfaces. Related dynamic phenomena, such as adiabatic shear localization. Applications to engineering phenomena and physics and mechanics of earthquakes. Instructor: Lapusta.

ANTHROPOLOGY

An 22. Introduction to Sociocultural Anthropology. *9 units (3-0-6); second, third terms.* Introduction to anthropological theory. Exploration of the diversity of human culture. Examination of the relationship between ecology, technology, and subsistence, patterns of marriage and residence, gender and sexual division of labor, reproduction, kinship, and descent. Links between economic complexity, population, social stratification, political organization, law, religion, ritual, and warfare are traced. Ethnic diversity and interethnic relations are surveyed. The course is oriented toward understanding the causes of cross-cultural variation and the evolution of culture. Instructor: Ensminger.

An 23. Human Evolution. *9 units (3-0-6); third term.* Introduction to human evolution, which is essential for understanding our species. Natural selection, sexual selection, genetics, systematics, behavioral ecology, and life history theory are covered. The order Primates is surveyed. Primary emphasis is on the hominid fossil and archeological record. Behavior, cognition, and culture of nonhuman primates and humans, as well as physical variation in present-day humans, is examined. Not offered 2010–11.

An 101. Selected Topics in Anthropology. *9 units (3-0-6); offered by announcement.* Not offered 2010–11.

An 135. Primate Behavior. *9 units (3-0-6); second term.* This course will examine how natural selection has shaped the social organization, life histories, reproductive strategies, social behavior, and cognitive abilities of nonhuman primates. It will review natural and sexual selection, examine the ecological and social pressures that shape primate behavior, and consider the role these principles play in shaping modern human behavior. Not offered 2010–11.

An/SS 142. Caltech Undergraduate Culture and Social Organization. *9 units (3-0-6); third term. Prerequisite: instructor's permission.* Students in this class will help develop hypotheses, methods, and background information for the design of a new class to be offered in subsequent years, which will seek to pose and empirically test questions related to cultural and social aspects of the Caltech undergraduate experience. Central to this project will be an examination of the theory of social networks and the role they play in the academic and social experience. Other qualitative and quantitative methods for future data gathering will also be designed. Not offered 2010–11.

An 150 ab. The Caltech Project. *9 units (3-0-6); second term. Prerequisite: instructor's permission*. Hands-on immersion in a social scientific research project examining the Caltech undergraduate community. Core data collection will use social network analysis. As channels of information flow, social networks are key determinants of career success, moral values, learning, diffusion of innovations, voting, disease transmission, and even terrorism. Few topics have drawn the interest of such diverse disciplines as anthropology, sociology, political science, economics, mathematics, medicine, biology, computer science, and physics. What can this and other methods teach us about the Caltech community? Instructor: Ensminger.

APPLIED AND COMPUTATIONAL MATHEMATICS

ACM 10. Introduction to Applied and Computational Mathematics. *1 unit (1-0-0); first term.* This course will introduce the research areas of the ACM faculty through weekly overview talks by the faculty aimed at first-year undergraduates. This course should be a useful introduction to ACM for those interested in possibly majoring in the option. Graded pass/fail. Instructor: Desbrun.

ACM 11. Introduction to Matlab and Mathematica. *6 units (2-2-2); first term. Prerequisites: Ma 1 abc, Ma 2 ab. CS 1 or prior programming experience recommended.* Matlab: basic syntax and development environment; debugging; help interface; basic linear algebra; visualization and graphical output; control flow; vectorization; scripts, and functions; file i/o; arrays, structures, and strings; numerical analysis (topics may include curve fitting, interpolation, differentiation, integration, optimization, solving nonlinear equations, fast Fourier transform, and ODE solvers); and advanced topics (may include writing fast code, parallelization, object-oriented features). Mathematica: basic syntax and the notebook interface, calculus and linear algebra operations, numerical and symbolic solution of algebraic and differential equations, manipulation of lists and expressions, Mathematica programming (rule-based, functional, and procedural) and debugging, plotting, and visualization. The course will also emphasize good programming habits and choosing the appropriate language/software for a given scientific task. Instructor: Tao.

ACM 95/100 abc. Introductory Methods of Applied Mathematics. *12 units (4-0-8); first, second, third terms. Prerequisites: Ma 1 abc, Ma 2 ab (may be taken concurrently), or equivalents.* First term: complex analysis: analyticity, Laurent series, singularities, branch cuts, contour integration, residue calculus. Second term: ordinary differential equations. Linear initial value problems: Laplace transforms, series solutions. Linear boundary value problems: eigenvalue problems, Fourier series, Sturm-Liouville theory, eigenfunction expansions, the Fredholm alternative, Green's functions, nonlinear equations, stability theory, Lyapunov functions, numerical methods. Third term: linear partial differential equations: heat equation separation of variables, Fourier transforms, special functions, Green's functions, wave equation, Laplace equation, method of characteristics, numerical methods. Instructors: Pierce, Bruno.

ACM 101. Methods of Applied Mathematics I. *9 units (3-0-6); second term. Prerequisite: ACM 95/100 abc.* Analytical methods for the formulation and solution of initial and boundary value problems for ordinary and partial differential equations. Techniques include the use of complex variables, generalized eigenfunction expansions, transform methods and applied spectral theory, linear operators, nonlinear methods, asymptotic and approximate methods, Weiner-Hopf, and integral equations. Taught concurrently with CDS 140 and AM 125. Instructors: Marsden, Murray.

ACM 104. Linear Algebra and Applied Operator Theory. *9 units (3-0-6); first term. Prerequisite: ACM 100 abc or instructor's permission.* Linear spaces, subspaces, spans of sets, linear independence, bases, dimensions; linear transformations and operators, examples, nullspace/kernel, range-space/image, one-to-one and onto, isomorphism and invertibility, rank-nullity theorem; products of linear transformations, left and right inverses, generalized inverses. Adjoints of linear transformations, singular-value decomposition and Moore-Penrose inverse; matrix representation of linear transformations between finite-dimensional linear spaces, determinants, multilinear forms; metric spaces: examples, limits and convergence of sequences, completeness, continuity, fixed-point (contraction) theorem, open and closed sets, closure; normed and Banach spaces, inner product and Hilbert spaces: examples, Cauchy-Schwarz inequality, orthogonal sets, Gram-Schmidt orthogonalization, projections onto subspaces, best approximations in subspaces by projection; bounded linear transformations, principle of superposition for infinite series, well-posed linear problems, norms of operators and matrices, convergence of sequences and series of operators; eigenvalues and eigenvectors of linear operators, including their properties for self-adjoint operators, spectral theorem for self-adjoint and normal operators; canonical representations of linear operators (finite-dimensional case), including diagonal and Jordan form, direct sums of (generalized) eigenspaces. Schur form; functions of linear operators, including exponential, using diagonal and Jordan forms, Cayley-Hamilton theorem. Taught concurrently with CDS 201. Instructor: Beck.

ACM 105. Applied Real and Functional Analysis. *9 units (3-0-6); second term. Prerequisite: ACM 100 abc or instructor's permission.* Lebesgue integral on the line, general measure and integration theory; Lebesgue integral in n-dimensions, convergence theorems, Fubini, Tonelli, and the transformation theorem; normed vector spaces, completeness, Banach spaces, Hilbert spaces; dual spaces, Hahn-Banach theorem, Riesz-Frechet theorem, weak convergence and weak solvability theory of boundary value problems; linear operators, existence of the adjoint. Self-adjoint operators, polar decomposition, positive operators, unitary operators; dense subspaces and approximation, the Baire, Banach-Steinhaus, open mapping and closed graph theorems with applications to differential and integral equations; spectral theory of compact operators; LP spaces, convolution; Fourier transform, Fourier series; Sobolev spaces with application to PDEs, the convolution theorem, Friedrich's mollifiers. Instructor: Yan.

ACM 106 abc. Introductory Methods of Computational Mathematics. *9 units (3-0-6); first, second, third terms. Prerequisites: Ma 1 abc, Ma 2 ab, ACM 11, ACM 95/100 abc or equivalent.* The sequence covers the introductory methods in both theory and implementation of numerical linear algebra, approximation theory, ordinary differential equations, and partial differential equations. The course covers methods such as direct and iterative solution of large linear systems; eigenvalue and vector computations; function minimization; nonlinear algebraic solvers; preconditioning; time-frequency transforms (Fourier, wavelet, etc.); root finding; data fitting; interpolation and approximation of functions; numerical quadrature; numerical integration of systems of ODEs (initial and boundary value problems); finite difference, element, and volume methods for PDEs; level set methods. Programming is a significant part of the course. Instructors: Schröder, Yan.

ACM 113. Introduction to Optimization. *9 units (3-0-6); second term. Prerequisites: ACM 95/100 abc, ACM 11, 104 or equivalent, or instruc-*

tor's permission. Unconstrained optimization: optimality conditions, line search and trust region methods, properties of steepest descent, conjugate gradient, Newton and quasi-Newton methods. Linear programming: optimality conditions, the simplex method, primal-dual interior-point methods. Nonlinear programming: Lagrange multipliers, optimality conditions, logarithmic barrier methods, quadratic penalty methods, augmented Lagrangian methods. Integer programming: cutting plane methods, branch and bound methods, complexity theory, NP complete problems. Instructor: Owhadi.

ACM/CS 114. Parallel Algorithms for Scientific Applications. *9 units (3-0-6); second term. Prerequisites: ACM 11, 106 or equivalent.* Introduction to parallel program design for numerically intensive scientific applications. Parallel programming methods; distributed-memory model with message passing using the message passing interface; shared-memory model with threads using open MP, CUDA; object-based models using a problem-solving environment with parallel objects. Parallel numerical algorithms: numerical methods for linear algebraic systems, such as LU decomposition, QR method, CG solvers; parallel implementations of numerical methods for PDEs, including finite-difference, finite-element; particle-based simulations. Performance measurement, scaling and parallel efficiency, load balancing strategies. Not offered 2010–11.

ACM/EE 116. Introduction to Stochastic Processes and Modeling. *9 units (3-0-6); first term. Prerequisite: Ma 2 ab or instructor's permission.* Introduction to fundamental ideas and techniques of stochastic analysis and modeling. Random variables, expectation and conditional expectation, joint distributions, covariance, moment generating function, central limit theorem, weak and strong laws of large numbers, discrete time stochastic processes, stationarity, power spectral densities and the Wiener-Khinchine theorem, Gaussian processes, Poisson processes, Brownian motion. The course develops applications in selected areas such as signal processing (Wiener filter), information theory, genetics, queuing and waiting line theory, and finance. Instructor: Tropp.

ACM/ESE 118. Methods in Applied Statistics and Data Analysis. *9 units (3-0-6); second term. Prerequisite: Ma 2 or another introductory course in probability and statistics.* Introduction to fundamental ideas and techniques of statistical modeling, with an emphasis on conceptual understanding and on the analysis of real data sets. Simple and multiple regression: estimation, inference, model checking. Analysis of variance, comparison of models, model selection. Principal component analysis. Linear discriminant analysis. Generalized linear models and logistic regression. Resampling methods and the bootstrap. Instructor: Schneider.

ACM 126 ab. Wavelets and Modern Signal Processing. *9 units (3-0-6); second, third terms. Prerequisites: ACM 11, 104, ACM 105 or undergraduate equivalent, or instructor's permission.* The aim is to cover the interactions existing between applied mathematics, namely applied and computational harmonic analysis, approximation theory, etc., and statistics and signal processing. The Fourier transform: the continuous Fourier transform, the discrete Fourier transform, FFT, time-frequency analysis, short-time Fourier transform. The wavelet transform: the continuous wavelet transform, discrete wavelet transforms, and orthogonal bases of wavelets. Statistical estimation. Denoising by linear filtering. Inverse problems. Approximation theory: linear/nonlinear approximation and applications to data compression. Wavelets and algorithms: fast wavelet transforms, wavelet packets, cosine packets, best orthogonal bases matching pursuit, basis pursuit. Data compression. Nonlinear estimation. Topics in stochastic processes. Topics in numerical analysis, e.g., multigrids and fast solvers. Not offered 2010–11.

Ma/ACM 142. Ordinary and Partial Differential Equations. *9 units (3-0-6).* For course description, see Mathematics.

Ma/ACM 144 ab. Probability. *9 units (3-0-6).* For course description, see Mathematics.

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

ACM 201 ab. Partial Differential Equations. *12 units (4-0-8); second, third terms. Prerequisite: ACM 11, 101 abc or instructor's permission.* Fully nonlinear first-order PDEs, shocks, eikonal equations. Classification of second-order linear equations: elliptic, parabolic, hyperbolic. Well-posed problems. Laplace and Poisson equations; Gauss's theorem, Green's function. Existence and uniqueness theorems (Sobolev spaces methods, Perron's method). Applications to irrotational flow, elasticity, electrostatics, etc. Heat equation, existence and uniqueness theorems, Green's function, special solutions. Wave equation and vibrations. Huygens' principle. Spherical means. Retarded potentials. Water waves and various approximations, dispersion relations. Symmetric hyperbolic systems and waves. Maxwell equations, Helmholtz equation, Schrödinger equation. Radiation conditions. Gas dynamics. Riemann invariants. Shocks, Riemann problem. Local existence theory for general symmetric hyperbolic systems. Global existence and uniqueness for the inviscid Burgers' equation. Integral equations, single- and double-layer potentials. Fredholm theory. Navier-Stokes equations. Stokes flow, Reynolds number. Potential flow; connection with complex variables. Blasius formulae. Boundary layers. Subsonic, supersonic, and transonic flow. Instructor: Hou.

ACM 210 ab. Numerical Methods for PDEs. *9 units (3-0-6); second, third terms. Prerequisite: ACM 11, 106 or instructor's permission.* Finite difference and finite volume methods for hyperbolic problems. Stability and error analysis of nonoscillatory numerical schemes: i) linear convection: Lax equivalence theorem, consistency, stability, convergence, truncation error, CFL condition, Fourier stability analysis, von Neumann condition, maximum principle, amplitude and phase errors, group velocity, modified equation analysis, Fourier and eigenvalue stability of systems, spectra and pseudospectra of nonnormal matrices, Kreiss matrix theorem, boundary condition analysis, group velocity and GKS normal mode analysis; ii) conservation laws: weak solutions, entropy conditions, Riemann problems, shocks, contacts, rarefactions, discrete conservation, Lax-Wendroff theorem, Godunov's method, Roe's linearization, TVD schemes, high-resolution schemes, flux and slope limiters, systems and multiple dimensions, characteristic boundary conditions; iii) adjoint equations: sensitivity analysis, boundary conditions, optimal shape design, error analysis. Interface problems, level set methods for multiphase flows, boundary integral methods, fast summation algorithms, stability issues. Spectral methods: Fourier spectral methods on infinite and periodic domains. Chebyshev spectral methods on finite domains. Spectral element methods and h-p refinement. Multiscale finite element methods for elliptic problems with multiscale coefficients. Instructor: Guo.

ACM 216. Markov Chains, Discrete Stochastic Processes and Applications. *9 units (3-0-6); second term. Prerequisite: ACM/EE 116 or equivalent.* Stable laws, Markov chains, classification of states, ergodicity, von Neumann ergodic theorem, mixing rate, stationary/equilibrium distributions and convergence of Markov chains, Markov chain Monte Carlo and its applications to scientific computing, Metropolis Hastings algorithm, coupling from the past, martingale theory and discrete time martingales, rare events, law of large deviations, Chernoff bounds. Instructor: Tropp.

ACM 217. Advanced Topics in Stochastic Analysis. *9 units (3-0-6); third term. Prerequisite: ACM 216 or equivalent.* The topic of this course changes from year to year and is expected to cover areas such as stochastic differential equations, stochastic control, statistical estimation and adaptive filtering, empirical processes and large deviation techniques, concentration inequalities and their applications. Examples of selected topics for stochastic differential equations include continuous time Brownian motion, Ito's calculus, Girsanov theorem, stopping times, and applications of these ideas to mathematical finance and stochastic control. Not offered 2010–11.

Ae/ACM/ME 232 abc. Computational Fluid Dynamics. *9 units (3-0-6).* For course description, see Aerospace.

ACM 256 ab. Special Topics in Applied Mathematics. *9 units (3-0-6); second, third terms. Prerequisite: ACM 101 or equivalent.* Introduction to finite element methods. Development of the most commonly used method—continuous, piecewise-linear finite elements on triangles for scalar elliptic partial differential equations; practical (a posteriori) error estimation techniques and adaptive improvement; formulation of finite element methods, with a few concrete examples of important equations that are not adequately treated by continuous, piecewise-linear finite elements, together with choices of finite elements that are appropriate for those problems. Homogenization and optimal design. Topics covered include periodic homogenization, G- and H-convergence, Gamma-convergence, G-closure problems, bounds on effective properties, and optimal composites. Not offered 2010–11.

ACM 257. Special Topics in Financial Mathematics. *9 units (3-0-6); third term. Prerequisite: ACM 95/100 or instructor's permission. A basic knowledge of probability and statistics as well as transform methods for solving PDEs is assumed.* This course develops some of the techniques of stochastic calculus and applies them to the theory of financial asset modeling. The mathematical concepts/tools developed will include introductions to random walks, Brownian motion, quadratic variation, and Ito-calculus. Connections to PDEs will be made by Feynman-Kac theorems. Concepts of risk-neutral pricing and martingale representation are introduced in the pricing of options. Topics covered will be selected from standard options, exotic options, American derivative securities, term-structure models, and jump processes. Not offered 2010–11.

ACM 270. Advanced Topics in Applied and Computational Mathematics. *Hours and units by arrangement; third term.* Advanced topics in applied and computational mathematics that will vary according to student and instructor interest. May be repeated for credit. Instructor: Owhadi.

ACM 290 abc. Applied and Computational Mathematics Colloquium. *1 unit; first, second, third terms.* A seminar course in applied and computational mathematics. Weekly lectures on current developments are presented by staff members, graduate students, and visiting scientists and engineers. Graded pass/fail only.

ACM 300. Research in Applied and Computational Mathematics. *Units by arrangement.*

APPLIED MECHANICS

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

CE/Ae/AM 108 abc. Computational Mechanics. *9 units (3-0-6).* For course description, see Civil Engineering.

AM 125 abc. Engineering Mathematical Principles. *9 units (3-0-6); first, second, third terms. Prerequisite: ACM 95/100 abc.* Topics include linear spaces, operators and matrices, integral equations, variational principles, ordinary and partial differential equations, stability, perturbation theory. Applications to problems in engineering and science are stressed. Instructor: Beck.

AM/CE 151 ab. Dynamics and Vibration. *9 units (3-0-6); first, second terms.* Equilibrium concepts, conservative and dissipative systems, Lagrange's equations, differential equations of motion for discrete single and multi degree-of-freedom systems, natural frequencies and mode shapes of these systems (Eigen value problem associated with the governing equations), phase plane analysis of vibrating systems, forms of damping and energy dissipated in damped systems, response to simple force pulses, harmonic and earthquake excitation, response spectrum concepts, vibration isolation, seismic instruments, dynamics of continuous systems, Hamilton's principle, axial vibration of rods and membranes, transverse vibration of strings, beams (Bernoulli-Euler and Timoshenko beam theory), and plates, traveling and standing wave solutions to motion of continuous systems, Rayleigh quotient and the Rayleigh-Ritz method to approximate natural frequencies and mode shapes of discrete and continuous systems, frequency domain solutions to dynamical systems, stability criteria for dynamical systems, and introduction to nonlinear systems and random vibration theory. Instructors: Heaton, Krishnan.

AM/ME 165 ab. Elasticity. *9 units (3-0-6); second, third terms. Prerequisites: Ae/Ge/ME 160 a and registered in Ae/Ge/ME 160 b.* Fundamental concepts and equations of elasticity. Linearized theory of elastostatics and elastodynamics: basic theorems and special solutions. Finite theory of elasticity: constitutive theory, semi-inverse methods. Variational methods. Applications to problems of current interest. Not offered 2010–11.

AM 200. Special Problems in Advanced Mechanics. *Hours and units by arrangement.* By arrangement with members of the staff, properly qualified graduate students are directed in independent studies in mechanics.

Ae/AM/MS/ME 213. Mechanics and Materials Aspects of Fracture. *9 units (3-0-6).* For course description, see Aerospace.

Ae/AM/CE/ME 214 abc. Computational Solid Mechanics. *9 units (3-0-6).* For course description, see Aerospace.

Ae/AM/ME 215. Dynamic Behavior of Materials. *9 units (3-0-6).* For course description, see Aerospace.

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

Ae/AM/ME 225. Special Topics in Solid Mechanics. *Units to be arranged.* For course description, see Aerospace.

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

Ch/APh 2. Introduction to Energy Sciences. *9 units (4-0-5).* For course description, see Chemistry.

APh/EE 9 ab. Solid-State Electronics for Integrated Circuits. *6 units (2-2-2); first, second terms; six units credit for the freshman laboratory requirement. Prerequisite: Successful completion of APh/EE 9 a is a prerequisite for enrollment in APh/EE 9 b.* Introduction to solid-state electronics, including physical modeling and device fabrication. Topics: semiconductor crystal growth and device fabrication technology, carrier modeling, doping, generation and recombination, pn junction diodes, MOS capacitor and MOS transistor operation, and deviations from ideal behavior. Laboratory includes computer-aided layout, and fabrication and testing of light-emitting diodes, transistors, and inverters. Students learn photolithography, and use of vacuum systems, furnaces, and device-testing equipment. Instructor: Scherer.

APh 17 abc. Thermodynamics. *9 units (3-0-6); first, second, third terms. Prerequisites: Ma 1 abc, Ph 1 abc.* Introduction to the use of thermodynamics and statistical mechanics in physics and engineering. Entropy, temperature, and the principal laws of thermodynamics. Canonical equations of state. Applications to cycles, engines, phase and chemical equilibria. Probability and stochastic processes. Kinetic theory of perfect gases. Statistical mechanics. Applications to gases, gas degeneration, equilibrium radiation, and simple solids. Instructors: Vahala, Crosignani.

APh 23. Demonstration Lectures in Optics. *6 units (2-0-4); second term. Prerequisite: Ph 1 abc.* This course cover fundamentals of optics with emphasis on modern optical applications, intended to exhibit basic optical phenomena including interference, dispersion, birefringence, diffraction, and laser oscillation, and the applications of these phenomena in optical systems employing two-beam and multiple-beam interferometry, Fourier-transform image processing, holography, electro-optic modulation, and optical detection and heterodyning. System examples to be selected from optical communications, radar, and adaptive optical systems. Instructor: Staff.

APh 24. Introductory Modern Optics Laboratory. *6 units (0-4-2); third term. Prerequisite: APh 23.* Laboratory experiments to acquaint students with the contemporary aspects of modern optical research and technology. Experiments encompass many of the topics and concepts covered in APh 23. Instructor: Staff.

APh 77 bc. Laboratory in Applied Physics. *9 units (0-9-0); second, third terms.* Selected experiments chosen to familiarize students with laboratory equipment, procedures, and characteristic phenomena in plasmas, fluid turbulence, fiber optics, X-ray diffraction, microwaves, high-temperature superconductivity, black-body radiation, holography, and computer interfacing of experiments. Instructor: Bellan.

APh 78 abc. Senior Thesis, Experimental. *9 units (0-9-0); first, second, third terms. Prerequisite: instructor's permission.* Supervised experimental research experience, open only to senior-class applied physics majors. Requirements will be set by individual faculty members, but will include a written report based upon actual laboratory experience. The selection of topic and the final report must be approved by the Applied Physics Undergraduate Committee. Students desiring additional units should register in APh 100. Not offered on a pass/fail basis. Instructor: Staff.

APh 79 abc. Senior Thesis, Theoretical. *9 units (0-9-0); first, second, third terms. Prerequisite: instructor's permission.* Supervised theoretical research experience, open only to senior-class applied physics majors. Requirements will be set by individual faculty members, but will include a written report based upon actual laboratory experience. The selection of topic and the final report must be approved by the Applied Physics Undergraduate Committee. Not offered on a pass/fail basis. This course cannot be used to satisfy the laboratory requirement in APh. Instructor: Staff.

APh 100. Advanced Work in Applied Physics. *Units in accordance with work accomplished.* Special problems relating to applied physics, arranged to meet the needs of students wishing to do advanced work. Primarily for undergraduates. Students should consult with their advisers before registering. Graded pass/fail.

Ae/APh/CE/ME 101 abc. Fluid Mechanics. *9 units (3-0-6).* For course description, see Aerospace.

Ae/APh 104 abc. Experimental Methods. *9 units (3-0-6 first term; 1-3-5 second, third terms).* For course description, see Aerospace.

APh 105 abc. States of Matter. *9 units (3-0-6); first, second, third terms. Prerequisite: APh 17 abc or equivalent.* A survey emphasizing unifying concepts, such as order parameters, scaling laws, quasi-particle excitations, and correlation functions. Topics: long-range ordered states such as crystals, superfluids, and ferromagnets; phase transitions; critical phenomena; ideal classical and degenerate gases; theory of liquids; band theory of solids; fluctuations; noise. Part c taught concurrently with MS 105. Instructors: Johnson, Fultz.

APh 109. Introduction to the Micro/Nanofabrication Lab. *9 units (0-6-3); first, second, third terms.* Introduction to techniques of micro- and nanofabrication, including solid-state, optical, and microfluidic devices. Students will be trained to use fabrication and characterization equipment available in the applied physics micro- and nanofabrication lab. Topics include Schottky diodes, MOS capacitors, light-emitting diodes, microlenses, microfluidic valves and pumps, atomic force microscopy, scanning electron microscopy, and electron-beam writing. Instructor: Ghaffari.

APh 110. Topics in Applied Physics. *2 units (2-0-0); first, second terms.* A seminar course designed to acquaint advanced undergraduates and first-year graduate students with the various research areas represented in the option. Lecture each week given by a different member of the APh faculty, who will review his or her field of research. Graded pass/fail. Instructor: Bellan.

APh 114 abc. Solid-State Physics. *9 units (3-0-6); first, second, third terms. Prerequisite: Ph 125 abc or equivalent.* Introductory lecture and problem course dealing with experimental and theoretical problems in solid-state physics. Topics include crystal structure, symmetries in solids, lattice vibrations, electronic states in solids, transport phenomena, semiconductors, superconductivity, magnetism, ferroelectricity, defects, and optical phenomena in solids. Instructors: Schwab, Atwater.

APh/Ph 115 ab. Physics of Transport in Fluids. *9 units (3-0-6); first, second terms. Prerequisite: ACM 95 or equivalent.* There is growing interest in micro- and nanodevices in which a solid surface is made to contact a fluid for the purpose of measurement or actuation. Such devices include oscillating cantilevers, microfluidic arrays, optofluidic devices, and biofluidic sensors, to name a few. This course provides a self-contained treatment of the fundamentals of transport phenomena necessary for the development of such applications. Topics to include creeping and pulsatile flows, self-similar phenomena, lubrication and free surface flows, oscillating bubbles, spreading films, convective-diffusion processes, and instabilities leading to pattern formation. The first term will focus on fluid dynamical principles; the second term will examine processes triggered by thermal or concentration gradients. Instructor: Troian.

APh/EE 130. Electromagnetic Theory. *9 units (3-0-6); first term.* This course reviews EM theory and optical concepts that are frequently encountered. EM theory: tensor matrix, kDB space, Poynting theorem. Dispersion and absorption. Reflection at an interface. Nonlinear optics. Polarization: Jones matrix and Stokes vectors. Ray tracing: ABCD matrix, optical aberrations. Noise. Diffraction. Interferometry: system design, homodyne, heterodyne, spectral domain analysis. Instructor: Yariv.

EE/APh 131. Optical Wave Propagation. *9 units (3-0-6).* For course description, see Electrical Engineering.

APh/EE 132. Optoelectronic Materials and Devices. *9 units (3-0-6); third term.* Interaction of light and matter, spontaneous and stimulated emission, laser rate equations, mode-locking, Q-switching, semiconductor lasers. Optical detectors and amplifiers; noise characterization of optoelectronic devices. Propagation of light in crystals, electro-optic effects and their use in modulation of light; introduction to nonlinear optics. Optical properties of nanostructures. Instructor: Yariv.

APh 150. Topics in Applied Physics. *Units to be arranged.* Content will vary from year to year, but at a level suitable for advanced undergraduate or beginning graduate students. Topics are chosen according to the interests of students and staff. Visiting faculty may present portions of this course. Not offered 2010–11.

APh 156 abc. Plasma Physics. *9 units (3-0-6); first, second, third terms. Prerequisite: Ph 106 abc or equivalent.* An introduction to the principles of plasma physics. A multitiered theoretical infrastructure will be developed consisting of the Hamilton-Lagrangian theory of charged particle motion in combined electric and magnetic fields, the Vlasov kinetic theory of plasma as a gas of interacting charged particles, the two-fluid model of plasma as interacting electron and ion fluids, and the magnetohydrodynamic model of plasma as an electrically conducting fluid subject to combined magnetic and hydrodynamic forces. This infrastructure will be used to examine waves, transport processes, equilibrium, stability, and topological self-organization. Examples relevant to plasmas in both laboratory (fusion, industrial) and space (magnetosphere, solar) will be discussed. Instructor: Bellan.

BE/APh 161. Physical Biology of the Cell. *12 units (3-0-9).* For course description, see Bioengineering.

BE/APh 162. Physical Biology Laboratory. *12 units (0-6-6).* For course description, see Bioengineering.

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

BE/APh/Ph 181. Biological Interfaces, Transduction, and Sensing. *9 units (3-0-6).* For course description, see Bioengineering.

APh/EE 183. Physics of Semiconductors and Semiconductor Devices. *9 units (3-0-6); third term.* Principles of semiconductor electronic structure, carrier transport properties, and optoelectronic properties relevant to semiconductor device physics. Fundamental performance aspects of basic and advanced semiconductor electronic and optoelectronic devices. Topics include energy band theory, carrier generation and recombination mechanisms, quasi-Fermi levels, carrier drift and diffusion transport, quantum transport. Instructor: Atwater.

APh 190 abc. Quantum Electronics. *9 units (3-0-6); first, second, third terms. Prerequisite: Ph 125 or equivalent.* Generation, manipulations, propagation, and applications of coherent radiation. The basic theory of the interaction of electromagnetic radiation with resonant atomic transitions. Laser oscillation, important laser media, Gaussian beam modes, the electro-optic effect, nonlinear-optics theory, second harmonic generation, parametric oscillation, stimulated Brillouin and

Raman scattering. Other topics include light modulation, diffraction of light by sound, integrated optics, phase conjugate optics, and quantum noise theory. Instructor: Painter.

APh 200. Applied Physics Research. *Units in accordance with work accomplished.* Offered to graduate students in applied physics for research or reading. Students should consult their advisers before registering. Graded pass/fail.

Ph/APh 223 abc. Advanced Condensed-Matter Physics. *9 units (3-0-6).* For course description, see Physics.

APh 250. Advanced Topics in Applied Physics. *Units and term to be arranged.* Content will vary from year to year; topics are chosen according to interests of students and staff. Visiting faculty may present portions of this course. Instructor: Staff.

APh 300. Thesis Research in Applied Physics. *Units in accordance with work accomplished.* APh 300 is elected in place of APh 200 when the student has progressed to the point where his or her research leads directly toward a thesis for the degree of Doctor of Philosophy. Approval of the student's research supervisor and department adviser or registration representative must be obtained before registering. Graded pass/fail.

ART HISTORY

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Art 11. Selected Topics in Art History. *9 units (3-0-6); offered by announcement.* Instructor: Staff.

Art 23. Major Figures in Art. *9 units (3-0-6); first term.* A course devoted to the study of a single artist of world importance, the name of the artist to be announced prior to registration. This study, grounded in the artist's life and, where possible, his/her writings, will analyze and interpret his/her major works in chronological sequence in their artistic and historic contexts, and attempt, by close aesthetic examination, to account for their greatness—and, sometimes, their failure. Not offered 2010–11.

Art 46. The Age of the Great Cathedrals. *9 units (3-0-6); third term.* A study of the arts of Western Europe from the disintegration of the Roman Empire circa A.D. 476, to the 14th century. The diverse historical forces at work during this long period produced a correspondingly varied art. Emphasis will be on the later Middle Ages, circa 1200–1350, a period marked by a synthesizing of inherited traditions into a comprehensive whole. Major monuments of architecture, such as the cathedrals of Notre Dame, Chartres, Reims, Cologne, Strasbourg, and Westminster, as well as sculpture, illuminated manuscripts, mosaics, panel painting, and stained glass will be examined within the aesthetic and social framework of countries as culturally diverse as France, Italy, Germany, Spain, and Britain. Not offered 2010–11.

Art 49. From Van Eyck to Rembrandt: Northern European Art, 1400–1650. *9 units (3-0-6); third term.* A survey of artistic developments in Northern Europe and Spain from the late Middle Ages through the Renaissance and baroque periods. The course will focus upon the complexity of northern art, from its origins in the still forceful medieval culture of 15th-century Flanders, to its confrontation with Italian Renaissance humanism in the 16th century. The effects of this cultural synthesis and the eventual development of distinct national schools of painting in the 17th century are examined through the works of the period's dominant artists, including Van Eyck, Dürer, Holbein, Velázquez, Rubens, Hals, and Rembrandt. Not offered 2010–11.

Art 50. Baroque Art. *9 units (3-0-6); first term.* A survey of the arts of painting, sculpture, and architecture from the late 16th century to the late 18th century. A confident and optimistic age, the baroque fostered the rise of national schools that produced artistic giants like Bernini, Caravaggio, Rubens, Rembrandt, Velázquez, Claude, Poussin, Tiepolo, and Guardi. The masterpieces of these and other artists reflect the wide variety of baroque art and will be studied within the context of certain commonly held ideals and of the differing economic, political, and religious systems that characterized the period. Not offered 2010–11.

Art 51. European Art of the 18th Century: From the Rococo to the Rise of Romanticism. *9 units (3-0-6); third term.* The course will encompass 18th-century European painting, sculpture, architecture, and the decorative arts. During this period a variety of styles and subjects proliferated in the arts, as seen in the richly diverse works of artists such as Watteau, Boucher, Chardin, Fragonard, Tiepolo, Canaletto, Hogarth, Gainsborough, Blake, David, Piranesi, and Goya, which reflect a new multiplicity in ways of apprehending the world. Instructor: Spieth.

Art 52. British Art. *9 units (3-0-6), third term.* A survey course on British painting, sculpture, and architecture in the 17th, 18th, and 19th centuries. By examining the works of well-known British artists such as Hogarth, Blake, Gainsborough, Reynolds, Constable, and Turner, the class will focus on the multiplicity of styles and themes that developed in the visual arts in Britain from 1740 to 1840 and are part of the wider artistic phenomenon known as romanticism. This introduction to the British visual arts will be enriched by several class meetings in the Huntington Art Gallery. Instructor: Bennett.

Art 55. Art of the 19th Century. *9 units (3-0-6); first term.* A survey of 19th-century art with an emphasis on French and English art between ca. 1770 and 1880. This course will focus on issues including competing conceptions of the public for art, the rise of photography, the development of the avant-garde, and the place of art in urban culture. Instructor: M. Hunter.

Art 66. Ancient Art: From the Pyramids to the Colosseum. *9 units (3-0-6); second term.* A survey of the art of the earliest civilization of the ancient near east and Mediterranean from the Bronze Age to A.D. 300. The major monuments—architectural, sculptural, and pictorial—of Mesopotamia, Egypt, the Aegean, Greece, and Rome will be examined as solutions to problems of form and function presented by communal political, economic, and religious life. Emphasis will be placed on the creation of Greco-Roman art, the foundation of the Western artistic tradition. Not offered 2010–11.

Art 67. Italian Renaissance Art. *9 units (3-0-6); first term.* A basic study of the greatest achievements of Italian painting, sculpture, and architecture in the 15th and 16th centuries. Masterpieces by a succession of artists such as Giotto, Masaccio, Brunelleschi, Donatello, Alberti, the Bellini, Leonardo da Vinci, Michelangelo, Raphael, Titian, Veronese, and others will be examined for their formal beauty and power, and studied as manifestations of individual genius in the context of their time and place: Italy, fragmented politically, yet at the peak of its cultural dominance. Not offered 2010–11.

Art 68. Modern Art. *9 units (3-0-6); third term.* An in-depth survey of international painting and sculpture of the first half of the 20th century. Crucial movements, among them fauvism, German expressionism, cubism, dadaism, surrealism, and American abstraction and realism between the two world wars, will be studied, and masterworks by a number of major artists of this period (e.g., Picasso, Matisse, Nolde, Duchamp, Magritte, Hopper) will be closely examined. Not offered 2010–11.

Art 70. Traditions of Japanese Art. *9 units (3-0-6), first term.* An introduction to the great traditions of Japanese art from prehistory through the Meiji Restoration (1868–1912). Students will examine major achievements of sculpture, painting, temple architecture, and ceramics as representations of each artistic tradition, whether native or adapted from foreign sources. Fundamental problems of style and form will be discussed, but aesthetic analysis will always take place within the conditions created by the culture. Instructor: Wolfgram.

Art 71. Arts of Buddhism. *9 units (3-0-6); third term.* An examination of the impact of Buddhism on the arts and cultures of India, Southeast Asia, China, Korea, and Japan from its earliest imagery in the 4th century B.C.E. India through various doctrinal transformations to the Zen revival of 18th-century Japan. Select monuments of Buddhist art, including architecture, painting, sculpture, and ritual objects, will serve as focal points for discussions on their aesthetic principles and for explorations into the religious, social, and cultural contexts that underlie their creation. Instructor: Wolfgram.

H/Art 119. Art Worlds. *9 units (3-0-6).* For course description, see History.

Art/H 155. Making and Knowing in Early Modern Europe. *9 units (3-0-6); first term.* This course examines interactions between art, science, and technological innovation in Europe and its colonies ca. 1500–1750. It will explore influential arguments that have linked the growth of empiricism in the sciences to naturalism in early modern visual art. Major topics may include the place of artistic training in scientific discovery, the "maker's knowledge" tradition, and relations of mind to body in early modern visual culture. Objects and images from local collections will be central to analysis. Not offered 2010–11.

Art 169. The Arts of Dynastic China. *9 units (3-0-6); second term.* A survey of the development of Chinese art in which the major achievements in architecture, sculpture, painting, calligraphy, and ceramics will be studied in their cultural contexts from prehistory through the Manchu domination of the Qing Dynasty (1644–1911). Emphasis will be placed on the aesthetic appreciation of Chinese art as molded by the philosophies, religions, and history of China. Not offered 2010–11.

Art/H 183. Spectacle: From the Court Masque to the Great Exhibition of 1851. *9 units (3-0-6); second term.* This course examines the ways in which spectacle has been used in early modern and nineteenth-century Europe. Drawing on aesthetic writings about the impact of size and scale on audiences, but also examining historical accounts of the workings of spectacle on spectators, it looks at a number of case studies focusing on the technologies spectacles employed, the sites at which they were staged, the purposes and aims of their creators, and the controversies they engendered. Topics covered include English court masques, the rituals of absolute monarchy (especially those of Louis XIV), the changing presentation of plays and works of art, the public exhibition of torture, punishment, and human dissection, cabinets of curiosity and scientific demonstrations, religious, civic, and political ritual commemoration, the development of mixed media, panoramas and dioramas, and the staging of international exhibitions. Instructor: Brewer.

ASTROPHYSICS

Ay 1. The Evolving Universe. *9 units (3-3-3); third term. This course is intended primarily for freshmen not expecting to take more advanced astronomy courses and will satisfy the menu requirement of the Caltech core curriculum.* Introduction to modern astronomy that will illustrate the accomplishments, techniques, and scientific methodology of contemporary astronomy. The course will be organized around a set of basic questions, showing how our answers have changed in response to fresh observational discoveries. Topics to be discussed will include telescopes, stars, planets, the search for life elsewhere in the universe, supernovae, pulsars, black holes, galaxies and their active nuclei, and the Big Bang. There will be a series of laboratory exercises intended to highlight the path from data acquisition to scientific interpretation. Students will also be required to produce a term paper on an astronomical topic of their choice and make a short oral presentation. In addition, a field trip to Palomar Observatory will be organized. Not offered on a pass/fail basis. Instructor: Scoville.

Ge/Ay 11 c. Planetary Sciences. *9 units (3-0-6).* For course description, see Geological and Planetary Sciences.

Ay 20. Basic Astronomy and the Galaxy. *10 units (3-1-6); first term. Prerequisites: Ma 1 abc, Ph 1 abc.* The electromagnetic spectrum; ground and space observing techniques; spectroscopy: inferring the composition and physical properties of astronomical objects; stellar masses, distances, and motions; the birth, structure, evolution, and death of stars; the structure and dynamics of the Galaxy. Short labs will introduce optics, spectroscopy, and astronomical measurement techniques. Instructor: A. Sargent.

Ay 21. Galaxies and Cosmology. *9 units (3-0-6); second term.* Cosmological models and parameters, extragalactic distance scale, cosmological tests; constituents of the universe, dark matter, and dark energy; thermal history of the universe, cosmic nucleosynthesis, recombination, and cosmic microwave background; formation and evolution of structure in the universe; galaxy clusters, large-scale structure and its evolution; galaxies, their properties and fundamental correlations; formation and evolution of galaxies, deep surveys; star formation history of the universe; quasars and other active galactic nuclei, and their evolution; structure and evolution of the intergalactic medium; diffuse extragalactic backgrounds; the first stars, galaxies, and the reionization era. Instructor: Phinney.

Ay 30. Introduction to Modern Research. *3 units (2-0-1); second term.* Weekly seminar open to declared Ay majors at the discretion of the instructor; nonmajors who have taken astronomy courses may be admitted. Course is intended for sophomores and juniors. This seminar is held in faculty homes in the evening and is designed to encourage student communication skills as they are introduced to faculty members and their research. Each week a student will review a popular-level article in astronomy for the class. Graded pass/fail. Instructor: A. Sargent.

Ay 31. Writing in Astronomy. *3 units; third term*. This course is intended to provide practical experience in the types of writing expected of professional astronomers. Example styles include research proposals, topical reviews, professional journal manuscripts, and articles for popular magazines such as *Astronomy or Sky and Telescope*. Each student will adopt one of these formats in consultation with the course instructor and write an original piece. An outline and several drafts reviewed by both a faculty mentor familiar with the topic and the course instructor are required. This course is open only to those who have taken upper-level astronomy courses. *Fulfills the Institute scientific writing requirement.* Instructor: Hillenbrand.

Ay 40. Topics in Modern Astrophysics. *6 units (2-0-4); third term. Prerequisite: Ay 20. May be repeated for credit.* The course covers the process of star formation from both observational and theoretical perspectives. Topics include star-forming regions, physical processes in molecular clouds, core collapse and protostars, premain sequence stars, the impact of star formation upon environment, theoretical evolutionary models, primordial accretion disks, formation of planetary systems, circumstellar debris disks, star formation on galactic scales. Not offered 2010–11.

Ay 43. Reading in Astronomy and Astrophysics. *Units in accordance with work accomplished, not to exceed 3.* Course is intended for students with a definite independent reading plan or who attend regular (biweekly) research and literature discussion groups. Instructor's permission required. Graded pass/fail.

Ay 78 abc. Senior Thesis. *9 units. Prerequisite: To register for this course, the student must obtain approval of the astronomy option representative and the prospective thesis adviser.* Open only to senior astronomy majors. Research must be supervised by a faculty member. The written thesis must be completed and approved by the adviser before the end of the third term. Students wishing assistance in finding an adviser and/or a topic for a senior thesis are invited to consult with the astronomy option representative. A grade will not be assigned in Ay 78 until the end of the third term. P grades will be given the first two terms, and then changed at the end of the course to the appropriate letter grade.

Ay 101. Physics of Stars. *11 units (3-2-6); first term. Prerequisite: Ay 20 is recommended.* Physics of stellar interiors and atmospheres. Properties of stars, stellar spectra, radiative transfer, line formation. Stellar structure, stellar evolution. Nucleosynthesis in stars. Stellar oscillations. Instructor: W. Sargent.

Ay 102. Physics of the Interstellar Medium. *9 units (3-0-6); second term. Prerequisite: Ay 20 is recommended.* An introduction to observations of the inter-stellar medium and relevant physical processes. The structure and hydrodynamic evolution of ionized hydrogen regions associated with massive stars and supernovae, thermal balance in neutral and ionized phases, star formation and global models for the interstellar medium. Instructor: Hirata.

Ay/Ph 104. Relativistic Astrophysics. *9 units (3-0-6); third term. Prerequisites: Ph 1, Ph 2 ab.* This course is designed primarily for junior and senior undergraduates in astrophysics and physics. It covers the physics of black holes and neutron stars, including accretion, particle acceleration and gravitational waves, as well as their observable consequenes: (neutron stars) pulsars, magnetars, X-ray binaries, gamma-ray bursts, gravity wave sources; (black holes) X-ray transients, quasars/active galaxies, and sources of low-frequency gravitatonal waves. Not offered 2010–11.

Ay 105. Optical Astronomy Instrumentation Lab. *10 units (0-6-4); third term. Prerequisite: Ay 20.* An opportunity for astronomy and physics undergraduates (juniors and seniors) to gain firsthand experience with the basic instrumentation tools of modern optical and infrared astronomy. The 10 weekly lab experiments are expected to include radiometry measurements, geometrical optics, optical aberrations and ray tracing, spectroscopy, fiber optics, CCD electronics, CCD characterization, photon counting detectors, vacuum and cryogenic technology, and stepper motors and encoders. Instructors: Hillenbrand, Johnson.

Ay 111 ab. Introduction to Current Astrophysics Research. *3 units; second, third terms.* This course is intended primarily for first-year Ay graduate students, although participation is open and encouraged. Students are required to attend seminar-style lectures given by astrophysics faculty members, describing their research, to attend the weekly astro-nomy colloquia, and to follow these with additional readings on the subject. At the end of each term, students are required to summarize in oral or written form (at the discretion of the instructor), one of the covered subjects that is of most interest to them. Instructors: Djorgovski, W. Sargent.

Ay 117. Statistics and Data Analysis in Astronomy. *9 units (3-0-6); first term.* In modern astronomy, vast quantities of data are often available to researchers. The challenge is converting this information into meaningful knowledge about the universe. The primary focus of this course is the development of a broad and general tool set that can be applied to the student's own research. We will use case studies from the astrophysical literature as our guide as we learn about common pitfalls, explore strategies for data analysis, understand how to select the best model for the task at hand, and learn the importance of properly quantifying and reporting the level of confidence in one's conclusions. We will have weekly homework assignments, much of which will be done in class in a collaborative work environment. Instructor: Johnson.

Ay 121. Radiative Processes. *9 units (3-0-6); first term. Prerequisite: Ph 125 or equivalent (undergraduates).* The interaction of radiation with matter: radiative transfer, emission, and absorption. Compton processes, synchrotron radiation, collisional excitation, spectroscopy of atoms and molecules. Instructor: Readhead.

Ay 122 ab. Astronomical Measurements and Instrumentation. *9 units (3-0-6); first, second terms. Prerequisite: Ph 106 or equivalent.* Measurement and signal analysis techniques throughout the electromagnetic spectrum with focus on infrared, optical, and ultraviolet techniques, on radio through submillimeter techniques, and on X-ray through gamma-ray techniques. Telescopes, optics, detectors, radiometers, photometry, spectroscopy. Active/adaptive optics. Interferometers/arrays. Imaging devices and image processing. Antennae, receivers, mixers, and amplifiers. Space telescopes. Probability and statistics as relevant to astronomical measurement. Some lab work and observatory field trips. Instructors: Steidel, Hillenbrand (a); Kulkarni (b).

Ay 123. Structure and Evolution of Stars. *9 units (3-0-6); first term. Prerequisites: Ay 101; Ph 125 or equivalent (undergraduates).* Thermodynamics, equation of state, convection, opacity, radiative transfer, stellar atmospheres, nuclear reactions, and stellar models. Evolution of low- and high-mass stars, supernovae, and binary stars. Instructors: Ellis, Cohen.

Ay 124. Structure and Dynamics of Galaxies. *9 units (3-0-6); second term. Prerequisites: Ay 21; Ph 106 or equivalent (undergraduates).* Stellar dynamics and properties of galaxies; kinematics and dynamics of our galaxy; spiral structure; stellar composition, masses, and rotation of external galaxies; star clusters; galactic evolution; binaries, groups, and clusters of galaxies. Instructors: Ellis, Djorgovski.

Ay 125. High-Energy Astrophysics. *9 units (3-0-6); third term. Prerequisites: Ph 106 and Ph 125 or equivalent (undergraduates).* High-energy astrophysics, Big Bang cosmology, the final stages of stellar evolution; supernovae, binary stars, accretion disks, pulsars; extragalactic radio sources; active galactic nuclei; black holes. Instructors: Ott, Weinstein.

Ay 126. Interstellar Medium. *9 units (3-0-6); second term. Prerequisite: Ay 102 (undergraduates).* Physical processes in the interstellar medium. Ionization, thermal and dynamic balance of interstellar medium, molecular clouds, hydrodynamics, magnetic fields, H II regions, supernova remnants, star formation, global structure of interstellar medium. Instructors: W. Sargent, Kamionskowski.

Ay 127. Cosmology and Galaxy Formation. *9 units (3-0-6); third term. Prerequisites: Ay 21; Ph 106 or equivalent (undergraduates).* Cosmology; extragalactic distance determinations; relativistic cosmological models; galaxy formation and clustering; thermal history of the universe, microwave background; nucleosynthesis; cosmological tests. Instructors: Djorgovski, Hirata.

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

Ge/Ay 133. The Formation and Evolution of Planetary Systems. *9 units (3-0-6).* For course description, see Geological and Planetary Sciences.

Ge/Ay 137. Planetary Physics. *9 units (3-0-6).* For course description, see Geological and Planetary Sciences.

Ay 141 abc. Research Conference in Astronomy. *3 units (1-0-2); first, second, third terms.* Oral reports on current research in astronomy, providing students an opportunity for practice in the organization and presentation of technical material. A minimum of two presentations will be expected from each student each year. In addition, students are encouraged to participate in a public-level representation of the same material for posting to an outreach website. This course fulfills the option communication requirement and is required of all astronomy graduate students who have passed their preliminary exams. It is also recommended for astronomy seniors. Graded pass/fail. Instructor: Staff.

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

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

Ge/Ay 159. Planetary Evolution and Habitability. *9 units (3-0-6).* For course description, see Geological and Planetary Sciences.

Ay 190. Computational Astrophysics. *9 units (3-0-6); second term. Prerequisites: Ph 20–22 (undergraduates).* Introduction to essential numerical analysis and computational methods in astrophysics and astrophysical data analysis. Basic numerical methods and techniques; N-body simulations; fluid dynamics (SPH/grid-based); MHD; radiation transport; reaction networks; data analysis methods; numerical relativity. Instructors: Ott, Benson.

Ay 199 ab. Special Topics in Astronomy and Astrophysics. *9 units (3-0-6); second, third terms.* Terms may be taken independently. Open to graduate and upper-division undergraduate students in all options. The topic for this year will be practical computational science methods that are useful in disciplines dealing with large and/or complex data sets. The course will cover scientific databases and archives; data mining and exploration; data visualization techniques; practical techniques for physical modeling, including numerical and stochastic models; data sharing over networks, Web services, computational and data grids; design and understanding of scientific computational systems and experiments, and good software practices. This course is the same as Bi 199 ab. Instructors: Djorgovski (a); Djorgovski, Phinney, Kamionkowski (b).

Ay 211. Extragalactic Astronomy. *9 units (3-0-6); first term. Prerequisites: Ay 123, Ay 124, and Ay 127.* Contemporary topics in extragalactic astronomy and cosmology, including observational probes of dark matter and dark energy; cosmological backgrounds and primordial element abundances; galaxy formation and evolution, including assembly histories, feedback and environmental effects; physics of the intergalactic medium; the role of active galactic nuclei; galactic structure and stellar populations; future facilities and their likely impact in the field. Not offered 2010–11.

Ay 215. Seminar in Theoretical Astrophysics. *9 units (3-0-6); second term.* Course for graduate students and seniors in astronomy and planetary science. Students will be required to lead some discussions. Topic will be selected based on student interest. Not offered 2010–11.

Ay 218. Extrasolar Planets and Stellar Seismology. *9 units (3-0-6); third term.* Close to 300 planets have been identified in orbit around normal stars. Astronomers are now embarking on understanding the statistics of extrasolar planet populations and characterizing with great precision individual planets, namely, determining their masses, radii, and in some cases, diagnosing their atmospheres. The successfully operating French mission COROT and the soon-to-be-launched NASA mission Kepler will dramatically increase the knowledge of extrasolar planets, primarily via their superb photometric precision. Such precision will also enable stellar seismology studies, as undertaken with the MOST satellite. These photometric missions will soon be followed by astrometric missions such as GAIA and SIM/PlanetQuest. The course will review the state of extrasolar planets, take up case studies, and anticipate findings. Not offered 2010–11.

Ay 219. Element Abundances from the Big Bang to the Present. *9 units (3-0-6); third term. Prerequisites: Ay 121, 123, 124, 126.* Survey of the formation of the elements in the universe as a function of cosmic time. Review of the determination of abundances in meteorites, stars, H II regions, and in interstellar and intergalactic gas using the electromagnetic spectrum from radio waves to X rays. Theory of nucleosynthesis in stars, supernovae and the Big Bang, including the s- and r-processes and explosive nucleosynthesis. Particular attention will be paid to the theory and observation of element synthesis in the "First Stars" in the universe. Emphasis will be placed on the connection between element synthesis, the initial mass function of star formation, and galactic evolution, including the role of galactic winds. Not offered 2010–11.

BIOCHEMISTRY AND MOLECULAR BIOPHYSICS

BMB/Bi/Ch 170 abc. Biochemistry and Biophysics of Macromolecules and Molecular Assemblies. *9 units (3-1-5); first, second, third terms. Prerequisite: Bi/Ch 110.* First term: detailed analysis of the structures of the four classes of biological molecules and the forces that shape them. Introduction to molecular biological and visualization techniques. Energetic principles and molecular mechanism of enzymatic catalysis. Practical kinetic techniques. Second term: basic principles of modern biophysical and structural methods to interrogate macromolecules from the atomic to cellular levels, including X-ray crystallography, NMR spectroscopy, molecular dynamics, electron and light microscopy, AFM, single molecule techniques, and systems biological simulations. Third term: detailed analysis of specific macromolecular machines and systems that illustrate the principles and biophysical methods taught in the first two terms. Instructors: Clemons, Jensen, Shan, staff.

BMB/Ch 178. Enzyme Kinetics and Mechanisms. *9 units (3-0-6); first term. Prerequisite: Bi/Ch 110 a or equivalent.* Discussion of the energetic principles and molecular mechanisms that underlie enzymes' enormous catalytic proficiency and exquisite specificity. Practical kinetics sections discuss how to infer molecular mechanisms from rate/equilibrium measurements and their application to more complex biological systems, and include steady-state and pre-steady-state kinetics, and kinetics at the single molecule level. Instructor: Shan.

BMB/Ch 202 abc. Biochemistry Seminar Course. *1 unit; first, second, third terms.* A course that includes a seminar on selected topics from outside faculty on recent advances in biochemistry. Students will participate in the seminar along with a formal discussion section with visiting faculty. Instructor: Clemons.

Bi/BMB 251 abc. Current Research in Cellular and Molecular Biology. *1 unit.* For course description, see Biology.

BMB 278. Fundamentals of Molecular Genetics. *9 units (3-0-6); third term.* Principles and mechanisms of DNA repair and replication, transcription and splicing, and protein synthesis. Not offered 2010–11.

BMB 299. Graduate Research. *Units to be arranged; first, second, third terms.* Students may register for research units after consultation with their adviser.

BIOENGINEERING

BE 1. Frontiers in Bioengineering. *1 unit; second term*. A weekly seminar series by Caltech faculty providing an introduction to research directions in the field of bioengineering. Graded pass/fail. Instructor: Pierce.

BE 98. Undergraduate Research in Bioengineering. *Variable units, as arranged with the advising faculty member; first, second, third terms.* Undergraduate research with a written report at the end of each term; supervised by a Caltech faculty member, or coadvised by a Caltech faculty member and an external researcher. Graded pass/fail. Instructor: Staff.

BE 100 abc. Bioengineering Lecture Series. *1 unit; first, second, third terms.* Required for first-year BE graduate students. Seminar series and training discussions with visiting speakers. Instructor: Staff.

BE 103. Biomedical Diagnostics and Therapeutics. *6 units (3-0-3); first term.* Transformative ideas in biomedicine and bioengineering have their origins in disciplines ranging from materials science, chemistry, and biology to optics, computation, and mechanical engineering. This course will survey the inspiration and development of some of the most significant innovations that have impacted biomedical science. Diagnostics will include landmark contributions such as magnetic resonance imaging (MRI), polymerase chain reaction (PCR), and radio immune assay (RIA). Therapeutics will include pharmaceutical agents, organ transplantation, implantable devices, and microsurgery. Not offered 2010–11.

BE 104. Biomechanics Research Lab. *9 units (1-3-5); third term.Prerequisite: Ae/APh 104 ab.* Design, execution, and analysis of an original experiment related to biomechanics and/or bioinspired design. Not offered 2010–11.

BE/Bi 105. Introduction to Biomechanics. *9 units (3-0-6); third term.* Introduction to the basic concepts of applying engineering principles of solid and fluid mechanics to the study of biological systems. The course emphasizes the organismal, rather than the molecular, level of complexity. It draws on a wide array of biological phenomena from plants and animals, and is not intended as a technical introduction to medically related biomechanics. Topics may include fundamental properties of solids and fluids, viscoelasticity, drag, biological pumps, locomotion, and muscle mechanics. Not offered 2010–11.

BE 141. Biomaterials: Science and Engineering. *9 units (3-0-6); first term. Prerequisites: Ph 2 ab or Ph 12 abc, Ch 1 ab, Ch 3 a, or instructor's permission. MS 115 ab recommended.* Lectures and experiments demonstrating the bulk and surface properties of materials; review of the major classes of materials—metals, ceramics, polymers—with a view to their relevance to the biomedical field. Special materials and processes of relevance will also be discussed, e.g., hydrogels, fabrics, thin films, bioresorbable and bioerodible materials, cardiac jelly, etc. Proteins, cells, tissues and their interactions with materials; key concepts in reactions between host materials and implants, including inflammation, coagulation, and tumorigenesis. Testing and degradation of biomaterials, material applications in medicine and dentistry, especially orthopedic, cardiovascular, ophthalmologic, oral and maxillofacial implants, and artificial organs. Instructor: Ravi.

BE 142. Biomaterials: Mechanical Properties. *9 units (3-0-6); third term. Prerequisite: BE 141 recommended.* Mechanical characteristics of biological and related materials with a focus on the development of constitutive relationships in the context of elastic, plastic, and viscoelastic materials; cell mechanics; bioviscoelasticity with relevance to actin, elastin, collagen, and soft tissues; mechanical behavior of blood vessels; mechanics of muscles including skeletal and heart muscles; bone and cartilage. Experimental techniques for the measurement of biological forces will also be discussed. Not offered 2010–11.

BE 151. Elementary Molecular and Cellular Principles. *9 units (3-0-6); first term.* This course is designed for bioengineering students with a limited background in molecular biology and cell physiology. The course will describe the physiology of eukaryotic cells at the molecular, organelle, and cellular levels, emphasizing visualization and manipulation techniques. Not offered 2010–11.

BE 152. The Physiology of Motion. *9 units (3-0-6); second term. Prerequisites: Bi 8, Bi 9, or equivalent*. This course emphasizes physiological mechanisms related to biological motility that operate at tissue- and organism-levels of complexity. The central theme of the class is to examine biological motility across levels of biological organization, from the gating properties of ion channels to the biomechanics of running, swimming, and flying. Topics include excitable membranes, oscillatory circuits, sensory feedback, muscle mechanics, cardiovascular physiology, and the biomechanics of locomotion. Instructor: Fraser.

BE 153. Case Studies in Systems Physiology. *9 units (3-0-6); third term. Prerequisites: Bi 8, Bi 9, or equivalent*. This course will explore the process of creating and validating theoretical models in systems biology and physiology. It will examine several macroscopic physiological systems in detail, including examples from immunology, endocrinology, cardiovascular physiology, and others. Emphasis will be placed on understanding how macroscopic behavior emerges from the interaction of individual components. Instructor: Petrasek.

BE 157. Modeling Spatiotemporal Pattern Formation in Complex Biological Systems. *9 units (3-0-6); second term. Prerequisites: Bi 8, Bi 9, ACM 95 abc, and Ph 2 b or Ph 12 c or Ch 25.* This course describes how to use statistical mechanics and nonlinear dynamics to model self-organized spatiotemporal pattern formation and transition kinetics in complex biological systems. These phenomena include Turing patterns in morphogenesis, oscillations by excitation-relaxation dynamics in cell signaling networks, and the propagation of traveling waves observed in action potentials and collective cell migration. This course emphasizes the construction of phenomenological models for stochastic nonlinear behavior in biological systems, including derivation of the corresponding Turing analysis, Langevin equation, Fokker-Planck equation, and Kramer theory. Instructor: Guo.

BE 159. Signal Transduction and Biomechanics in Eukaryotic Cell Morphogenesis. *9 units (3-0-6); third term. Prerequisites: Bi 8, Bi 9, ACM 95 abc.* This course examines the mechanical and biochemical pathways that govern eukaryotic cell morphogenesis. Topics include embryonic pattern formation, cell polarization and migration in tissue development and regeneration. Biomechanics will be treated at the molecular, cellular, and multicellular levels of organization. In addition to providing background material on cytoskeletal biomechanics and intra/intercellular signaling in cell-matrix and cell-cell interactions, the course will emphasize the interplay between mechanical and biochemical pathways in tissue morphogenesis and homeostasis. Current understanding of malignant transformation will be briefly described, as well. The course will briefly introduce appropriate modeling techniques and tools such as fabrication and optical approaches to the quantitative study of morphogenesis. Instructor: Guo.

BE/APh 161. Physical Biology of the Cell. *12 units (3-0-9); second term. Prerequisites: limited to juniors and seniors who have completed the required BE courses; background in statistical and quantum mechanics or instructor's written permission required.* Physical models applied to the analysis of biological structures ranging from individual proteins and DNA to entire cells. Topics include the force response of proteins and DNA, models of molecular motors, DNA packing in viruses and eukaryotes, mechanics of membranes, and membrane proteins and cell motility. Instructor: Phillips.

BE/APh 162. Physical Biology Laboratory. *12 units (0-6-6); second term. Prerequisites: concurrent enrollment in BE/APh 161; limited to juniors and seniors who have completed the required BE courses.* This laboratory course accompanies BE/APh 161 and is built around experiments that amplify material covered in that course. Particular topics include background on techniques from molecular biology, mechanics of lipid bilayer vesicles, DNA packing in viruses, fluorescence microscopy of cells, experiments on cell motility, and the construction of genetic networks. Not offered 2010–11.

ChE/BE 163. Introduction to Biomolecular Engineering. *9 units (3-0-6).* For course description, see Chemical Engineering.

EE/BE 166. Optical Methods for Biomedical Imaging and Diagnosis. *9 units (3-1-5).* For course description, see Electrical Engineering.

BE 167. Topics in Bioengineering. *1 unit; first term. Required for first-year graduate BE students.* Introduction to the current research in bioengineering and related fields, focusing specifically on projects carried out by Caltech faculty. The course will provide the students with background within the lecturer's specific discipline. Instructor: Pierce.

ChE/BE 169. Biomolecular Cell Engineering. *9 units (3-0-6).* For course description, see Chemical Engineering.

Bi/BE 177. Principles of Modern Microscopy. *9 units (3-0-6).* For course description, see Biology.

BE/APh/Ph 181. Biological Interfaces, Transduction, and Sensing. *9 units (3-0-6); third term. Prerequisites: APh 105, Ph129 or equivalent (students without a background in statistical physics are still encouraged to take the course—additional tutorial sessions will be arranged as needed).* Basic physics and chemical physics of interfaces between the fundamental realm of biology—molecules and cells—and the physical world. The course centers on processes that are essential for transduction to energy domains in which modern sensors operate. Information transfer from the biological realm to optical, electronic, and mechanical domains will be considered. Particular attention will be paid to both the sensitivity and the kinetics of transduction processes, and to how fluctuations affect and ultimately impose fundamental limits on such interactions. Instructor: Roukes.

EE/BE 185. MEMS Technology and Devices. *9 units (3-0-6).* For course description, see Electrical Engineering.

BE/EE 189 ab. Design and Construction of Biodevices. *12 units (3-6-3) first term; 9 units (0-9-0) second term; first, second terms. Prerequisite: ACM 95 ab (for BE/EE 189 a); BE/EE 189 a (for BE/EE 189 b).* First term, students will design and implement biosensing systems, including a pulse monitor, a pulse oximeter, and a real-time polymerase-chain-reaction incubator. Students will learn to program in LABVIEW. Second term is a student-initiated design project requiring instructor's permission for enrollment. Enrollment is limited to 24 students. *BE/EE 189 a is an option requirement; second term is not.* Instructor: C. Yang.

BE/CS/CNS/Bi 191 ab. Biomolecular Computation. *9 units (3-0-6) second term; (2-4-3) third term. Prerequisite: ChE/BE 163. Recommended: CS 21, CS 129 ab, or equivalent.* This course investigates computation by molecular systems, emphasizing models of computation based on the underlying physics, chemistry, and organization of biological cells. We will explore programmability, complexity, simulation of and reasoning about abstract models of chemical reaction networks, molecular folding, molecular self-assembly, and molecular motors, with an emphasis on universal architectures for computation, control, and construction within molecular systems. If time permits, we will also discuss biological example systems such as signal transduction, genetic regulatory networks, and the cytoskeleton; physical limits of computation, reversibility, reliability, and the role of noise, DNA-based computers and DNA nanotechnology. Part a develops fundamental results; part b is a reading and research course: classic and current papers will be discussed, and students will do projects on current research topics. Instructor: Winfree.

BE 200. Research in Bioengineering. *Units and term to be arranged.* By arrangement with members of the staff, properly qualified graduate students are directed in bioengineering research.

Bi/BE 227. Methods in Modern Microscopy. *12 units (2-6-4).* For course description, see Biology.

BE 240. Special Topics in Bioengineering. *Units and term to be arranged.* Topics relevant to the general educational goals of the bioengineering option. Graded pass/fail.

Ae/BE 242. Biological Flows: Propulsion. *9 units (3-0-6).* For course description, see Aerospace.

BE/Ae 243. Biological Flows: Transport and Circulatory Systems. *9 units (3-0-6); third term. Prerequisite: Ae/APh/CE/ME 101 abc or equivalent or ChE 103 a.* Internal flows: steady and pulsatile blood flow in compliant vessels, internal flows in organisms. Fluid dynamics of the human circulatory system: heart, veins, and arteries (microcirculation). Mass and momentum transport across membranes and endothelial layers. Fluid mechanics of the respiratory system. Renal circulation and circulatory system. Biological pumps. Not offered 2010–11.

BE/CNS 248. Magnetic Resonance Imaging. *9 units (3-1-5); first term. Prerequisites: Undergraduate-level physics, biology, and/or engineering courses recommended; basic quantum mechanics, statistics, and signal processing are helpful.* Physics, engineering, and computational aspects of MRI. Theory, engineering, and practice of MRI for biological and medical applications are covered in detail. Provides technical background necessary for a full understanding of the concepts underpinning the specific uses of MRI for functional brain imaging. Complements CNS/SS 251. Not offered 2010–11.

Bi/BE 250 c. Topics in Systems Biology. *9 units (3-0-6).* For course description, see Biology.

BE 262. Physical and Synthetic Biology Boot Camp. *9 units (1-8-0); summer.* This course provides an intensive research introduction to current projects in physical and synthetic biology. Projects are based on current research directions in participating labs, including those of visiting biologists invited for the course. Representative classes of experiments include quantitative fluorescent microscopy of cell and organelle dynamics, single-cell measurement of genetic expression levels during development, and design and construction of biological circuits in microbes. Graded pass/fail. Instructor: Phillips.

BIOLOGY

Bi 1. The Biology and Biophysics of Viruses. *9 units (4-0-5); third term.* This course introduces nonbiologists to recent advances in our understanding of how HIV and other viruses infect and cause damage to their hosts. Because understanding and treating HIV infection involves a basic knowledge of cell and molecular biology, virology, and immunology, the course will cover fundamental concepts in these areas from a quantitative, molecular, chemical, and biophysical perspective. Instructor: Bjorkman.

Bi 1 x. The Great Ideas of Biology: An Introduction through Experimentation. *9 units (0-6-3); third term.* Introduction to concepts and laboratory methods in biology. Molecular biology techniques and advanced microscopy will be combined to explore the great ideas of biology. This course is intended for nonbiology majors and will satisfy the freshman biology course requirement. Limited enrollment. Instructor: Phillips.

Bi 2. Current Research in Biology. *6 units (2-0-4); first term. Intended for students considering the biology option; open to freshmen.* Current research in biology will be discussed, on the basis of reading assigned in advance of the discussions, with members of the divisional faculty. Graded pass/fail. Instructor: Elowitz.

Bi 8. Introduction to Molecular Biology: Organization and Expression of Genetic Information. *9 units (3-0-6); second term.* This course and its sequel, Bi 9, cover biology at the cellular level. After introducing basic concepts necessary for understanding biological systems at the molecular level, Bi 8 emphasizes cellular processes involved in the organization and expression of genetic information, including what is commonly called molecular biology, and introduces topics in developmental biology and immunology. Instructor: Rothenberg.

Bi 9. Cell Biology. *9 units (3-0-6); third term.* Continues coverage of biology at the cellular level, begun in Bi 8. Topics: cytoplasmic structure, membrane structure and function, cell motility, and cell-cell recognition. Emphasis on both the ultrastructural and biochemical approaches to these topics. Instructors: Aravin, Deshaies.

Bi 10. Cell Biology Laboratory. *6 units (1-3-2); third term. Prerequisite: Bi 8; designed to be taken concurrently with Bi 9.* Introduction to basic methods in cell and molecular biological research, including polymerase chain reaction, molecular cloning, expression and purification of recombinant fusion proteins in bacteria, enzymology, and gel electrophoresis of proteins and nucleic acids. Instructor: Deshaies.

Bi 22. Undergraduate Research. *Units to be arranged; first, second, third terms.* Special problems involving laboratory research in biology; to be arranged with instructors before registration. Graded pass/fail. Instructor: Staff.

Bi 23. Biology Tutorial. *Units to be arranged; usually 3, maximum of 6 units per term; second term.* Small group study and discussion in depth of special areas or problems in biology, involving regular tutorial sections with instructors. To be arranged with instructors before registration. Graded pass/fail. Instructor: Huang.

Bi 24. Technical Communication for Biologists. *6 units (2-0-4); first term.* This course offers instruction and practice in writing and speaking relevant to professional biologists working in research, teaching, and/or medical careers. Students may write a paper for a scientific journal, based on their previous research and mentored by a faculty member. Alternatively, students may produce a variety of brief writing assignments with a range of audiences and purposes. Oral presentations will be based on writing produced in the course, with feedback from instructors and peers. *Fulfills the Institute scientific writing requirement.* Instructors: Jensen, Youra, Marsen.

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

CNS/SS/Psy/Bi 102 ab. Brains, Minds, and Society. *9 units (3-0-6).* For course description, see Computation and Neural Systems.

Ph/Bi 103 b. Neuroscience for Physicists and Engineers. *9 units (3-0-6).* For course description, see Physics.

BE/Bi 105. Introduction to Biomechanics. *9 units (3-0-6).* For course description, see Bioengineering.

Bi/Ch 110. Introduction to Biochemistry. *12 units (4-0-8); first term. Prerequisite: Ch 41 abc or instructor's permission.* Lectures and recitation introducing the molecular basis of life processes, with emphasis on the structure and function of proteins. Topics will include the derivation of protein structure from the information inherent in a genome, biological catalysis, the intermediary metabolism that provides energy to an organism, and the use of DNA manipulations, cloning, and expression of proteins in foreign hosts to study protein structure and function. Instructors: Richards, Campbell.

Bi/Ch 111. Biochemistry of Gene Expression. *12 units (4-0-8); second term. Prerequisites: Bi/Ch 110; Bi 8 and Bi 122 recommended.* Lectures and recitation on the molecular basis of biological structure and function. Emphasizes the storage, transmission, and expression of genetic information in cells. Specific topics include DNA replication, recombination, repair and mutagenesis, transcription, RNA processing, and protein synthesis. Instructors: Campbell, Parker.

Bi/Ch 113. Biochemistry of the Cell. *12 units (4-0-8); third term. Prerequisites: Bi/Ch 110; Bi 9 recommended.* Lectures and recitation on the biochemistry of basic cellular processes in the cytosol and at the cell surface, with emphasis on signal transduction, membrane trafficking, and control of cell division. Specific topics include cell-cell signaling, control of gene expression by cell surface molecules, tumorigenesis, endocytosis, exocytosis, viral entry, and cell cycle regulation. Instructor: Chan.

Bi 114. Immunology. *9 units (3-0-6); second term. Prerequisites: Bi 8, Bi 9, Bi 122 or equivalent, and Bi/Ch 110 recommended.* The course will cover the molecular and cellular mechanisms that mediate recognition and response in the mammalian immune system. Topics include cellular and humoral immunity, the structural basis of immune recognition, antigen presentation and processing, developmental regulation of gene rearrangement, biochemistry of lymphocyte activation, lymphokines and the regulation of cellular responses, T and B cell development, and mechanisms of tolerance. Instructor: Mazmanian.

Bi 115. Attack and Repulsion: Viruses and their Hosts. *6 units (2-0-4); spring term.* The course will introduce the chemistry and biology of viruses, emphasizing their diverse replication strategies. It will then focus on mechanisms used by viruses to multiply in the face of host defenses. It will also discuss cancer-inducing viruses. The course will mainly consider mammalian viruses but will also discuss aspects of plant and bacterial viruses. Instructor: Baltimore. Given in alternate years; not offered 2010–11.

Bi 117. Developmental Biology. *9 units (3-0-6); second term. Prerequisites: Bi 8 and Bi 9.* A survey of the development of multicellular organisms. Topics will include the beginning of a new organism (fertilization), the creation of multicellularity (cellularization, cleavage), reorganization into germ layers (gastrulation), induction of the nervous system (neurulation), and creation of specific organs (organogenesis). Emphasis will be placed on the molecular mechanisms underlying morphogenetic movements, differentiation, and interactions during development, covering both classical and modern approaches to studying these processes. Instructor: Bronner-Fraser.

CNS/Bi/Psy 120. The Neuronal Basis of Consciousness. *9 units (4-0-5).* For course description, see Computation and Neural Systems.

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

Bi 123. Genetics Laboratory. *12 units (2-8-2); second term. Prerequisite: Bi 122.* Laboratory exercises illustrating the principles of genetics, with emphasis on Mendelian inheritance in multicellular eukaryotes, including *Drosophila melanogaster* and *Caenorhabditis elegans.* Instructors: Hay, staff.

Bi 129. Biology of Cancer. *9 units (3-0-6); first term.* The first part of the course will concern the basic biology of cancer, covering oncogenes, tumor suppressors, tumor cell biology, metastasis, tumor angiogenesis, and other topics. There will also be a section on cancer genetics, which will primarily be taught from primary literature and journal reviews. The last part of the course will concern treatments, including chemotherapy, anti-angiogenic therapy, and immunotherapy. Textbook: *The Biology of Cancer* (2006) by Robert Weinberg. Instructor: Zinn. Given in alternate years; offered 2010–11.

CNS/Psy/Bi 131. The Psychology of Learning and Motivation. *9 units (3-0-6).* For course description, see Computation and Neural Systems.

Bi/Ch 132. Biophysics of Macromolecules. *9 units (3-0-6); first term. Recommended prerequisite: Bi/Ch 110.* Structural and functional aspects of nucleic acids and proteins, including hybridization; electrophoretic behavior of nucleic acids; principles and energetics of folding of polypeptide chains in proteins; allostery and cooperativity in protein action; enzyme kinetics and mechanisms; and methods of structure determination, such as X-ray diffraction and magnetic resonance. Structure and function of metalloenzymes. Instructors: Beauchamp, Rees.

Bi 145 ab. Tissue and Organ Physiology. *9 units (4-0-5); first, second terms. Prerequisites: Bi 8, 9, 110, 117. Bi 110 may be taken concurrently.* Reviews of embryology, anatomy, and histology, as well as in-depth discussion of cellular physiology (from a control and digital logic perspective). Topics will include building from cell function to tissues, hematologic, connective tissue, musculoskeletal physiology, and integration of these tissue functions into the function of the cardiovascular system. Cardiovascular system in an organ-based fashion, with pulmonary, renal, gastrointestinal, hepatobiliary, neuroendocrine, and reproductive physiology. Specific topics in advanced physiology, including cardiovascular and pulmonary physiology, exercise, nutrition, congenital abnormalities, selected topics in pathophysiology. Instructors: Fraser, Pierce.

Bi 146. Human Anatomy. *9 units (4-0-5); second term. Prerequisites: Bi 8, Bi 9.* Introduction to human anatomy and histology. For biology majors interested in premed. May be taken concurrently with Bi 145. Topics include musculoskeletal, neural, cardiovascular, pulmonary, gastrointestinal, renal, endocrine and reproductive anatomy. Virtual labs required. Not offered 2010–11.

Bi/CNS 150. Introduction to Neuroscience. *10 units (4-0-6); first term. Prerequisites: Bi 8, 9, or instructors' permission.* General principles of the function and organization of nervous systems, providing both an overview of the subject and a foundation for advanced courses. Topics include the physical and chemical bases for action potentials, synaptic transmission, and sensory transduction; anatomy; development; sensory and motor pathways; memory and learning at the molecular, cellular, and systems level; and the neuroscience of brain diseases. Instructors: Adolphs, Lester.

Bi 152. Introduction to Neuroethology. *6 units (2-0-4); second term.* Introduction to the neurobiological study of natural behavior of animals. Topics include such questions as how animals recognize and localize signals in their natural environments, how animals move, how behavior develops, what and how animals learn, and how natural selection shapes the evolution of brain and behavior. Instructor: Konishi.

Bi 156. Molecular Basis of Behavior. *9 units (3-0-6); second term. Prerequisite: Bi 150 or instructor's permission.* A lecture and discussion course on the neurobiology of behavior. Topics may include biological clocks, eating behavior, sexual behavior, addiction, mental illness, and neurodegenerative diseases. Instructor: Patterson. Given in alternate years; not offered 2010–11.

Bi/CNS 157. Comparative Nervous Systems. *9 units (2-3-4); third term.* An introduction to the comparative study of the gross and microscopic structure of nervous systems. Emphasis on the vertebrate nervous system; also, the highly developed central nervous systems found in arthropods and cephalopods. Variation in nervous system structure with function and with behavioral and ecological specializations and the evolution of the vertebrate brain. Instructor: Allman. Given in alternate years; offered 2010–11.

Bi/CNS 158. Vertebrate Evolution. *9 units (3-0-6); third term.* An integrative approach to the study of vertebrate evolution combining comparative anatomical, behavioral, embryological, genetic, paleontological, and physiological findings. Special emphasis will be given to: (1) the modification of developmental programs in evolution; (2) homeostatic systems for temperature regulation; (3) changes in the life cycle governing longevity and death; (4) the evolution of brain and behavior. Instructor: Allman. Given in alternate years; not offered 2010–11.

Bi/CNS 162. Cellular and Systems Neuroscience Laboratory. *12 units (2-7-3); third term. Prerequisite: Bi 150 or instructor's permission.* A laboratory-based introduction to experimental methods used for electrophysiological studies of the central nervous system. Through the term, students investigate the physiological response properties of neurons in insect and mammalian brains, using extra- and intracellular recording techniques. Students are instructed in all aspects of experimental procedures, including proper surgical techniques, electrode fabrication, stimulus presentation, and computer-based data analysis. Graded pass/fail. Instructor: Wagenaar.

ESE/Bi 166. Microbial Physiology. *9 units (3-1-5).* For course description, see Environmental Science and Engineering.

ESE/Bi 168. Microbial Metabolic Diversity. *9 units (3-0-6).* For course description, see Environmental Science and Engineering.

BMB/Bi/Ch 170 abc. Biochemistry and Biophysics of Macromolecules and Molecular Assemblies. *9 units (3-1-5).* For course description, see Biochemistry and Molecular Biophysics.

CNS/Bi/SS/Psy 176. Cognition. *12 units (6-0-6).* For course description, see Computation and Neural Systems.

Bi/BE 177. Principles of Modern Microscopy. *9 units (3-0-6); first term.* Lectures and discussions on the underlying principles behind digital, video, differential interference contrast, phase contrast, confocal, and two-photon microscopy. The course will begin with basic geometric optics, characteristics of lenses and microscopes, and principles of accurate imaging. Specific attention will be given to how different imaging elements such as filters, detectors, and objective lenses contribute to the final image. Course work will include critical evaluation of published images and design strategies for simple optical systems. Emphasis in the second half of the course will be placed on the analysis and presentation of two- and three-dimensional images. No prior knowledge of microscopy will be assumed. Instructor: Fraser.

Bi 180. Methods in Molecular Genetics. *12 units (2-8-2); first term. Prerequisites: Bi 122, Bi 10, or instructor's permission.* An introduction to current molecular genetic techniques including basic microbiological procedures, transposon and UV mutagenesis, gene transfer, preparation of DNA, restriction, ligation, electrophoresis (including pulsed-field), electroporation, Southern blotting, PCR, gene cloning, sequencing, and computer searches for homologies. The first half of the course involves structured experiments designed to demonstrate the various techniques. The second half is devoted to individual research projects in which the techniques are applied to original studies on an interesting, but not well studied, organism. Graded pass/fail. Instructor: Bertani.

Bi 182. Developmental Gene Regulation and Evolution of Animals. *6 units (2-0-4); second term. Prerequisites: Bi 8 and at least one of the following: Bi 111, Bi 114, or Bi 122 (or equivalents).* Lectures on and discussion of the regulatory genome; phylogenetic relationships in animals and the fossil record; how developmental gene regulation works; regulatory basis of development in the simplest systems; making parts of the adult animal body plan; pattern formation and deep regulatory networks; the Precambrian world and a gene-regulatory view of the evolutionary origin of animal forms; processes of *cis*-regulatory evolution; diversification in the arthropods; and the special character of vertebrate evolution. Instructors: Davidson, Stathopoulos.

Bi/CNS 184. The Primate Visual System. *9 units (3-1-5); third term.* This class focuses on the primate visual system, investigating it from an experimental, psychophysical, and computational perspective. The course will focus on two essential problems: 3-D vision and object recognition. Topics include parallel processing pathways, functional specialization, prosopagnosia, object detection and identification, invariance, stereopsis, surface perception, scene perception, navigation, visual memory, multidimensional readout, signal detection theory, oscillations, and synchrony. It will examine how a visual stimulus is represented starting in the retina, and ending in the frontal lobe, with a special emphasis placed on mechanisms for high-level vision in the parietal and temporal lobes. The course will include a lab component in which students design and analyze their own fMRI experiment. Instructor: Tsao.

CNS/Bi/EE 186. Vision: From Computational Theory to Neuronal Mechanisms. *12 units (4-4-4).* For course description, see Computation and Neural Systems.

CNS/Bi/Ph/CS 187. Neural Computation. *9 units (3-0-6).* For course description, see Computation and Neural Systems.

Bi 188. Human Genetics and Genomics. *6 units (2-0-4); third term. Prerequisite: Bi 122; or graduate standing and instructor's permission.* Introduction to the genetics of humans. Subjects covered include human genome structure, genetic diseases and predispositions, the human genome project, forensic use of human genetic markers, human variability, and human evolution. Given in alternate years; offered 2010–11.

Bi 189. The Cell Cycle. *6 units (2-0-4); third term. Prerequisites: Bi 8 and Bi 9.* The course covers the mechanisms by which eukaryotic cells control their duplication. Emphasis will be placed on the biochemical processes that ensure that cells undergo the key events of the cell cycle in a properly regulated manner. Instructor: Dunphy.

Bi 190. Advanced Genetics. *6 units (2-0-4); third term. Prerequisite: Bi 122.* Lectures and discussions covering advanced principles of genetic analysis. Emphasis on genetic approaches to the study of development in *Saccharomyces*, *Caenorhabditis*, *Drosophila*, and *Arabidopsis*. Instructor: Sternberg. Given in alternate years; offered 2010–11.

BE/CS/CNS/Bi 191 ab. Biomolecular Computation. *9 units.* For course description, see Bioengineering.

Bi 199 ab. Special Topics in Computational Biology. *9 units (3-0-6); second, third terms.* Terms may be taken independently. Open to graduate and upper-division undergraduate students in all options. The topic for this year will be practical computational science methods that are useful in disciplines dealing with large and/or complex data sets. The course will cover scientific databases and archives; data mining and exploration; data visualization techniques; practical techniques for physical modeling, including numerical and stochastic models; data sharing over networks, Web services, computational and data grids; design and understanding of scientific computational systems and experiments, and good software practices. This course is the same as Ay 199 ab. Instructors: Djorgovski, Kennedy, CACR staff.

Bi 202. Neurobiology of Disease. *9 units (3-0-6); first term. Prerequisite: Bi 150 or instructor's permission.* This course will cover the cellular and molecular basis of diseases of the nervous system, as well as current and future therapeutic approaches. These diseases include disorders of abnormal protein structure (Alzheimer's, Huntington's, Parkinson's, prion), autoimmunity (multiple sclerosis), and developmental disorders of cognition and social communication (schizophrenia, autism). Genetic and environmental etiologies will be explored, and animal models will be compared to the human condition. The role of the reward system in addiction will also be discussed. Instructor: Patterson. Given in alternate years; offered 2010–11.

Bi 204. Evolution of the Animal Body Plan. *6 units (2-0-4); third term. Prerequisite: Bi 182 or equivalent. Qualified undergraduates are welcome.* Evolution of animal forms will be considered mechanistically in terms of change in the genomic regulatory programs underlying the developmental ontogeny of these forms, but within the framework provided by current concepts of animal phylogeny. Evolutionary mechanisms will be considered, as well, with respect to the real-time paleontological record and the changing conditions of Earth's environment through geological time. Principles emerging from the system biology of regulatory evolution will be emphasized. Instructor: Davidson.

Bi 206. Biochemical and Genetic Methods in Biological Research. *6 units (2-0-4); third term. Prerequisite: graduate standing or instructor's permission.* This course will comprise in-depth discussions of selected methods in molecular biology and related fields. Given the enormous range of techniques available to a molecular biologist nowadays, the course will focus on a subset of these methods that includes recent and highly promising techniques, with an emphasis on their robustness and general applicability. Instructor: Varshavsky.

Bi 214. Hematopoiesis: A Developmental System. *6 units (2-0-4); third term. Prerequisite: Bi 114, or Bi 182, or Bi 117 plus Bi/Ch 111, or graduate standing.* An advanced course with lectures and seminar presentations, based on reading from the current literature. The characteristics of blood cells offer unique insights into the molecular basis of lineage commitment and the mechanisms that control the production of diverse cell types from pluripotent precursors. The course will cover the nature of stem cells, the lineage relationships among differentiated cell types, the role of cytokines and cytokine receptors, apoptosis and lineage-specific proliferation, and how differentiation works at the level of gene regulation and regulatory networks. Roles of prominent regulatory molecules in hematopoietic development will be compared with their roles in other developmental systems. Emphasis will be on explanation of cellular and system-level phenomena in terms of molecular mechanisms. Instructor: Rothenberg. Given in alternate years; offered 2010–11.

Bi/CNS 216. Behavior of Mammals. *6 units (2-0-4); first term.* A course of lectures, readings, and discussions focused on the genetic, physiological, and ecological bases of behavior in mammals. A basic knowledge of neuroanatomy and neurophysiology is desirable. Instructor: Allman. Given in alternate years; not offered 2010–11.

Bi/CNS 217. Central Mechanisms in Perception. *6 units (2-0-4); first term.* Reading and discussions of behavioral and electrophysiological studies of the systems for the processing of sensory information in the brain. Instructor: Allman. Given in alternate years; offered 2010–11.

Bi 218. Molecular Neurobiology Graduate Seminar. *6 units (2-0-4); second term.* Topics to be announced. Instructor: Anderson. Given in alternate years; not offered 2010–11.

CNS/Bi 221. Computational Neuroscience. *9 units (4-0-5).* For course description, see Computation and Neural Systems.

Bi/CNS 220. Genetic Dissection of Neural Circuit Function. *6 units (2-0-4); third term.* This advanced course will discuss the emerging science of neural "circuit breaking" through the application of molecular genetic tools. These include optogenetic and pharmacogenetic manipulations of neuronal activity, genetically based tracing of neuronal connectivity, and genetically based indicators of neuronal activity. Both viral and transgenic approaches will be covered, and examples will be drawn from both the invertebrate and vertebrate literature. Interested students who have little or no familiarity with molecular biology will be supplied with the necessary background information. Lectures and student presentations from the current literature. Instructor: Anderson. Given in alternate years; offered 2010–11.

Bi/BE 227. Methods in Modern Microscopy. *12 units (2-6-4); second term. Prerequisite: instructor's permission.* Discussion and laboratory-based course covering the practical use of the confocal microscope, with special attention to the dynamic analysis of living cells and embryos. Course will begin with basic optics, microscope design, Koehler illumination, and the principles of confocal microscopy. After introductory period, the course will consist of semi-independent weeklong modules organized around different imaging challenges. Early modules will focus on three-dimensional reconstruction of fixed cells and tissues, with particular attention being paid to accurately imaging very dim samples. Later modules will include time-lapse confocal analysis of living cells and embryos, including *Drosophila*, zebra fish, chicken, and *s* embryos. Dynamic analysis will emphasize the use of fluorescent proteins. No prior experience with confocal microscopy will be assumed; however, a basic working knowledge of microscopes is highly recommended. Preference is given to graduate students who will be using confocal microscopy in their research. Instructor: Fraser.

Ch/Bi 231. Advanced Topics in Biochemistry. *6 units (2-0-4).* For course description, see Chemistry.

Ge/Bi 244. Paleobiology Seminar. *6 units (3-0-3).* For course description, see Geological and Planetary Sciences.

Ge/Bi 246. Molecular Geobiology Seminar. *6 units (2-0-4).* For course description, see Geological and Planetary Sciences.

CNS/Bi 247. Cerebral Cortex. *6 units (2-0-4).* For course description, see Computation and Neural Systems.

Bi 250 a. Topics in Molecular and Cellular Biology. *9 units (3-0-6); first term. Prerequisite: graduate standing.* Lectures and discussion covering research methods, logic, techniques and strategies, fundamental and general principles of modern biology, and unsolved problems. Students will learn to critique papers on molecular biology, cell biology, and genetics. Instructor: Prober.

Bi/CNS 250 b. Topics in Systems Neuroscience. *9 units (3-0-6); third term. Prerequisite: graduate standing.* The class focuses on quantitative studies of problems in systems neuroscience. Students will study classical work such as Hodgkin and Huxley's landmark papers on the ionic basis of the action potential, and will move from the study of interacting currents within neurons to the study of systems of interacting neurons. Topics will include lateral inhibition, mechanisms of motion tuning, local learning rules and their consequences for network structure and dynamics, oscillatory dynamics and synchronization across brain circuits, and formation and computational properties of topographic neural maps. The course will combine lectures and discussions, in which students and faculty will examine papers on systems neuroscience, usually combining experimental and theoretical/modeling components. Instructor: Siapas.

Bi/BE 250 c. Topics in Systems Biology. *9 units (3-0-6); second term. Prerequisite: graduate standing.* The class will focus on quantitative studies of cellular and developmental systems in biology. It will examine the architecture of specific genetic circuits controlling microbial behaviors and multicellular development in model organisms. The course will approach most topics from both experimental and theoretical/computational perspectives. Specific topics include chemotaxis, multistability and differentiation, biological oscillations, stochastic effects in circuit operation, as well as higher-level circuit properties such as robustness. The course will also consider the organization of transcriptional and protein-protein interaction networks at the genomic scale. Instructor: Elowitz.

Bi/BMB 251 abc. Current Research in Cellular and Molecular Biology. *1 unit. Prerequisite: graduate standing.* Presentations and discussion of research at Caltech in biology and chemistry. Discussions of responsible conduct of research are included. Instructors: Sternberg, Hay.

Bi 252. Responsible Conduct of Research. *4 units (2-0-2); third term.* This lecture and discussion course covers relevant aspects of the responsible conduct of biomedical and biological research. Topics include guidelines and regulations, ethical and moral issues, research misconduct, data management and analysis, research with animal or human subjects, publication, conflicts of interest, mentoring, and professional advancement. This course is required of all trainees supported on the NIH training grants in cellular and molecular biology and neuroscience, and is recommended for other graduate students in biology division labs. Undergraduate students require advance instructor's permission. Graded pass/fail. Instructors: Meyerowitz, Sternberg, staff.

SS/Psy/Bi/CNS 255. Topics in Emotion and Social Cognition. *9 units (3-0-6).* For course description, see Social Science.

CNS/Bi 256. Decision Making. *6 units (2-0-4).* For course description, see Computation and Neural Systems.

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

CNS/Bi 286 abc. Special Topics in Computation and Neural Systems. *Units to be arranged.* For course description, see Computation and Neural Systems.

Bi 299. Graduate Research. *Units to be arranged; first, second, third terms.* Students may register for research units after consultation with their adviser.

BUSINESS ECONOMICS AND MANAGEMENT

BEM/Ec/SS 20. Scientific Writing and Oral Presentation in the Social Sciences. *6 units (2-0-4); second term.* This class provides the opportunity for students to improve their written and oral presentation skills in the social sciences. Students should come prepared with complete drafts of papers from another course or a SURF project, which they will substantially revise and improve in a style typical of peer-reviewed journals in their discipline. These papers must be the students' original work and must be papers with social science content. An initial introduction to the art of scientific writing will be provided by the staff of the Hixon Writing Center. In addition, each student will work closely with an HSS mentor whose own research is close to the student's paper topic. *Fulfills the Institute scientific writing requirement and the option oral presentation requirement for HSS majors.* Instructors: Yariv, Daley.

BEM 101. Introduction to Accounting. *9 units (3-0-6); first, second terms.* An introduction to accounting in business. Topics include financial accounting, cost accounting. Instructor: Wang.

BEM 103. Introduction to Finance. *9 units (3-0-6); first term. Ec 11 recommended.* An introduction to corporate finance. Economic theory is used to study asset valuation and financial decision making in business. Topics include financial decision making under certainty, introduction to valuation of risky assets (stocks and bonds), the corporate investment decision, dividend policy, and the corporate financing decision. Instructor: Bossaerts.

BEM 104. Investments. *9 units (3-0-6); second term. Prerequisites: Ec 11, BEM 103, some familiarity with statistics.* Examines the theory of financial decision making and statistical techniques useful in analyzing financial data. Topics include portfolio selection, equilibrium security pricing, empirical analysis of equity securities, fixed-income markets, market efficiency, and risk management. Instructor: Gillen.

BEM 105. Options. *9 units (3-0-6); second term. Prerequisites: BEM 103, some familiarity with statistics. Ec 11 recommended.* An introduction to modern option pricing theory. The focus is the valuation of contingent claims. Both American and European options are considered. The binomial and Black-Scholes option pricing models are derived. The theory is also applied to risky debt and portfolio choice. Instructor: Cvitanic.

BEM 106. Competitive Strategy. *9 units (3-0-6); third term. Prerequisite: Ec 11.* This course develops concepts appropriate for formulating strategy in a competitive environment, using a combination of case analysis and lectures. The course covers differentiation strategies, positioning to neutralize incumbency advantages, the product life cycle, organizational design as competitive strategy, signaling, cooperation strategies, pricing and price discrimination as competitive strategy, strategic use of option theory, and the war of attrition. Not offered 2010–11.

BEM 107. Advanced Corporate Finance: Governance, Transacting, and Valuation. *9 units (3-0-6); third term. Prerequisite: BEM 103.* This course builds on the concepts introduced in BEM 103 and applies them to current issues related to the financial management, regulation, and governance of both ongoing corporations and new start-up companies. The fundamental theme is valuation. The course discusses how valuation is affected by, among others, the role of directors, regulation of mergers and acquisitions, and management incentives. Instructor: Cornell.

BEM 109. Fixed-Income and Credit-Risk Derivatives. *9 units (3-0-6); third term. Prerequisite: BEM 105.* An introduction to the models of interest rates and credit/default risk. The focus is on continuous time models used in Wall Street practice for pricing and hedging fixed income securities. Two main models for credit risk are considered: structural and reduced form. Not offered 2010–11.

BEM 110. Venture Capital. *9 units (3-0-6); first term. Prerequisites: BEM 101, 103.* An introduction to the theory and practice of venture capital and start-ups. This course covers the underlying economic principles and theoretical models relevant to the venture investment process, as well as the standard practices used by industry. Special attention is paid to the organization, funding, management, and growth of start-up companies. Not offered 2010–11.

BEM 111. Risk Management. *9 units (3-0-6); third term. Prerequisites: BEM 103, 105.* An introduction to financial risk management. Concepts of Knightian risk and uncertainty; coherent risk; and commonly used metrics for risk. Techniques for estimating equity risk; volatility; correlation; interest rate risk; and credit risk are described. Discussions of fat-tailed (leptokurtic) risk, scenario analysis, and regime-switching methods provide an introduction to methods for dealing with risk in extreme environments. Instructor: Winston.

BEM 116. Advanced Business Strategy for Technology. *9 units (3-0-6); third term. Prerequisite: BEM 106.* This course develops tools to determine strategy for firms facing rapid technological change, great uncertainty, low marginal costs and high fixed costs of production, and short product life cycles. The focus is on firms with high levels of human capital (so-called high-tech firms). Special attention is paid to the product life cycle, patent strategy, pricing, and hiring and retention of talented individuals. Working in teams, students will be asked to formulate strategy in real business situations. Not offered 2010–11.

BEM/Ec 118. Environmental Economics. *9 units (3-0-6); second term. Prerequisite: Ec 11 or equivalent.* This course provides a survey from the perspective of economics of public policy issues regarding the management of natural resources and the protection of environmental quality. The course covers both conceptual topics and recent and current applications. Included are principles of environmental and resource economics, management of nonrenewable and renewable resources, and environmental policy with the focus on air pollution problems, both local problems (smog) and global problems (climate change). Instructor: Ledyard.

BEM/PS 126. Business and Public Policy. *9 units (3-0-6); first term. Prerequisite: PS 12 or equivalent*. This class studies the relationships among business, government, and interest groups as strategic actors in the nonmarket environment. Methods of influencing public policy are analyzed using the tools of modern political theory and ethical frameworks. Topics may include media, private collective action, international business, and corporate social responsibility. Knowledge of basic political and economic theory will be useful. Not offered 2010–11.

BEM/Ec 146. Organization Design. *9 units (3-0-6); second term. Prerequisite: Ec 11*. An introduction to the analysis, design, and management of organizations with an emphasis on incentives and information. Principles from economics, political science, and game theory will be applied to problems in project and team management, in organizational computing, and in allocating and pricing shared facilities. Instructor: Camerer.

BEM/Ec 185. Political Economy of Corporate Governance. *9 units (3-0-6); first term. Prerequisite: PS/Ec 172.* The course covers issues of how firms are organized. Topics include the distribution of power and returns among shareholders, managers, and other stakeholders; the role of law, public policy, and financial markets in constraining or enabling firms to solve the problems they face; the interaction between history, financial market structure, and the ownership of very large firms. Not offered 2010–11.

BEM/Ec 187. Corporate Finance and Financial Intermediaries. *9 units (3-0-6); third term. Prerequisites: Ec 11, BEM 103.* This course will cover the institutions, problems, and methods encountered financing business and public enterprises. After reviewing the classical theory of corporation finance, we will consider the information and tax problems facing firms seeking financing, how the need for financial intermediation arises, the process of issuing securities, IPOs, and the sources of financial crises. Implications for both corporate and public policy will be discussed. Instructor: Green.

BEM 190. Undergraduate Research Project. *Units to be arranged; any term. Prerequisites: BEM 103, 106, and instructor's permission.* This course offers advanced undergraduates the opportunity to pursue research on a business problem individually or in small groups. Graded pass/fail.

CHEMICAL ENGINEERING

ChE 10. Introduction to Chemical Engineering. *3 units (2-0-1); second term; open to freshmen only.* A series of weekly seminars given by chemical engineering faculty or an outside speaker, on a topic of current research. Topics will be presented at an informal, introductory level. Graded pass/fail.

ChE 63 ab. Chemical Engineering Thermodynamics. *9 units (3-0-6); second, third terms.* A comprehensive treatment of classical thermodynamics with engineering and chemical applications and an introduction to statistical thermodynamics. First and second laws. Applications to closed and open systems. Equations of state. Thermochemical calculations. Properties of real fluids. Power generation and refrigeration cycles. Multicomponent systems, excess properties, fugacities, activity coefficients, and models of nonideal solutions. Chemical potential. Phase and chemical reaction equilibria. Introductory statistical thermodynamics. Instructors: Tirrell, Flagan.

ChE 64. Principles of Chemical Engineering. *9 units (3-0-6); first term.* Systems approach to conservation of mass and energy. Equilibrium staged separations. Instructor: Seinfeld.

ChE 80. Undergraduate Research. *Units by arrangement.* Research in chemical engineering offered as an elective in any term other than in the senior year. Graded pass/fail.

ChE 90 ab. Senior Thesis. *9 units (0-4-5); first, second, third terms.* A research project carried out under the direction of a chemical engineering faculty member. The project must contain a significant design component. Students must submit a proposal by the beginning of the first term of the thesis for review and approval. A grade will not be assigned prior to completion of the thesis, which normally takes two terms. A P grade will be given for the first term and then changed to the appropriate letter grade at the end of the course.

Ch/ChE 91. Scientific Writing. *3 units (2-0-1).* For course description, see Chemistry.

ChE 101. Chemical Reaction Engineering. *9 units (3-0-6); second term. Prerequisites: ChE 63 ab and ChE 64, or instructor's permission.* Elements of chemical kinetics and chemically reacting systems. Homogeneous and heterogeneous catalysis. Chemical reactor analysis. Instructor: Arnold.

ChE 103 abc. Transport Phenomena. *9 units (3-0-6); first, second, third terms. Prerequisite: ACM 95/100 abc or concurrent registration, or instructor's permission.* A rigorous development of the basic differential equations of conservation of momentum, energy, and mass in fluid systems. Solution of problems involving fluid flow, heat transfer, and mass transfer. Instructors: Vicic, Kornfield, Davis.

ChE 105. Dynamics and Control of Chemical Systems. *9 units (3-0-6); third term. Prerequisites: ChE 101 and ACM 95 abc or concurrent registration, or instructor's permission.* Analysis and design of dynamic chemical systems, spanning biomolecular networks to chemical processing. Topics include control strategies for regulating dynamic performance, formulation of mechanistic and empirical models, linear analysis of feedback systems, introduction to multivariate control. Instructor: Seinfeld.

ChE 115. Electronic Materials Processing. *9 units (3-0-6); third term. Prerequisites: ChE 63 ab, ChE 103 abc, ChE 101, or instructor's permission.* After a brief introduction to solid-state concepts, materials, and devices relevant to electronic applications, the course will cover the prevalent growth and etching techniques used in processing of electronic materials. Emphasis is on the underlying physical and chemical principles. Crystal and thin film growth techniques to be covered include physical and chemical vapor deposition, liquid-phase epitaxy, molecular beam epitaxy, and plasma-assisted deposition. Property altering processes such as diffusion, oxidation, and doping are also included. Plasma etching is introduced with emphasis on determining key parameters that control the ion energy and flux to the wafer surface. Key techniques for thin film analysis and characterization are briefly discussed. Instructor: Giapis. Given in alternate years; offered 2010–11.

ChE 118. Introduction to the Design of Chemical Systems. *9 units (3-0-6); second term. Prerequisites: ChE 63 ab, ChE 101, ChE 103 abc, ChE 126, or instructor's permission.* Short-term, open-ended projects that require students to design a chemical process or product. Each team generates and filters ideas, identifies use cases and objectives, evaluates and selects a design strategy, develops a project budget, schedules milestones and tasks, and writes a proposal with supporting documentation. Each project must meet specified requirements for societal impact, budget, duration, person hours, environmental impact, safety, and ethics. Instructor: Vicic.

ChE 120. Optimal Design of Chemical Systems. *9 units (1-6-2); third term. Prerequisites: ChE 63 ab, ChE 101, ChE 103 abc, ChE 126, or instructor's permission.* Short-term, open-ended projects that require students to design and build a chemical process or manufacture a chemical product. Each team selects a project after reviewing a collection of proposals. Students use chemical engineering principles to design, build, test, and optimize a system, component, or product that fulfills specified performance requirements, subject to constraints imposed by budget, schedule, logistics, environmental impact, safety, and ethics. Instructor: Vicic.

ChE 126. Chemical Engineering Laboratory. *9 units (1-6-2); first term. Prerequisites: ChE 63 ab, ChE 101, ChE 103, ChE 105, or instructor's permission.* Short-term projects that require students to work in teams to design systems or system components. Projects typically include unit operations and instruments for chemical detection. Each team must identify specific project requirements, including performance specifications, costs, and failure modes. Students use chemical engineering principles to design, implement, and optimize a system (or component) that fulfills these requirements, while addressing issues and constraints related to environmental impact, safety, and ethics. Students also learn professional ethics through the analysis of case studies. Instructor: Vicic.

ChE 128. Chemical Engineering Design Laboratory. *9 units (1-6-2); second term. Prerequisites: ChE 63 ab, ChE 101, ChE 103, or instructor's permission.* Short-term, open-ended research projects targeting chemical processes in microreactors. Projects include synthesis of chemical products or materials, detection and destruction of environmental pollutants, and other gas phase conversions. Each student is required to construct and troubleshoot his/her own microreactor, then experimentally evaluate and optimize independently the research project using chemical engineering principles. Where possible, cost analysis of the optimized process is performed. Instructors: Vicic, Giapis.

ChE 130. Biomolecular Engineering Laboratory. *9 units (1-5-3); third term. Prerequisites: ChE 63 ab, ChE 101 (concurrently) or instructor's permission.* Design, construction, and characterization of engineered biological systems that will be implemented in bacteria, yeast, and cell-free systems. Research problems will fall into the general areas of biomolecular engineering and synthetic biology. Emphasis will be on projects that apply rational and evolutionary design strategies toward engineering biological systems that exhibit dynamic, logical, or programmed behaviors. Instructors: Tirrell, Vicic.

Ch/ChE 140 ab. Principles and Applications of Semiconductor Photoelectrochemistry. *9 units (3-0-6).* For course description, see Chemistry.

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

ChE/Ch 148. Polymer Physics. *9 units (3-0-6); third term.* An introduction to the physics that govern polymer structure and dynamics in liquid and solid states, and to the physical basis of characterization methods used in polymer science. The course emphasizes the scaling aspects of the various physical properties. Topics include conformation of a single polymer chain under different solvent conditions; dilute and semi-dilute solutions; thermodynamics of polymer blends and block copolymers; rubber elasticity; polymer gels; linear viscoelasticity of polymer solutions and melts; glass transition and crystallization. Instructor: Wang. Given in alternate years; offered 2010–11.

ChE 151 ab. Physical and Chemical Rate Processes. *12 units (3-0-9); first, second terms.* The foundations of heat, mass, and momentum transfer for single and multiphase fluids will be developed. Governing differential equations; laminar flow of incompressible fluids at low and high Reynolds numbers; forced and free convective heat and mass transfer, diffusion, and dispersion. Emphasis will be placed on physical understanding, scaling, and formulation and solution of boundary-value problems. Applied mathematical techniques will be developed and used throughout the course. Instructor: Brady.

ChE 152. Heterogeneous Kinetics and Reaction Engineering. *9 units (3-0-6); first term. Prerequisite: ChE 101 or instructor's permission.* Survey of heterogeneous reactions and reaction mechanisms on metal and oxide catalysts. Characterization of porous catalysts. Reaction, diffusion, and heat transfer in heterogeneous catalytic systems. Instructor: Davis.

ChE/Ch 155. Chemistry of Catalysis. *9 units (3-0-6); third term.* Discussion of homogeneous and heterogeneous catalytic reactions, with emphasis on the relationships between the two areas and their role in energy problems. Topics include catalysis by metals, metal oxides, zeolites, and soluble metal complexes; utilization of hydrocarbon resources;

and catalytic applications in alternative energy approaches. Instructors: Davis, Labinger. Given in alternate years; not offered 2010–11.

ChE/ESE 158. Aerosol Physics and Chemistry. *9 units (3-0-6); second term. Open to graduate students and seniors with instructor's permission.* Fundamentals of aerosol physics and chemistry; aerodynamics and diffusion of aerosol particles; condensation and evaporation; thermodynamics of particulate systems; nucleation; coagulation; particle size distributions; optics of small particles. Instructor: Seinfeld.

ChE/BE 163. Introduction to Biomolecular Engineering. *9 units (3-0-6); first term. Prerequisites: Bi/Ch 110 or instructor's permission.* The course introduces rational design and evolutionary methods for engineering functional protein and nucleic acid systems. Rational design topics include molecular modeling, positive and negative design paradigms, simulation and optimization of equilibrium and kinetic properties, design of catalysts, sensors, motors, and circuits. Evolutionary design topics include evolutionary mechanisms and tradeoffs, fitness landscapes, directed evolution of proteins, and metabolic pathways. Some assignments require programming (MATLAB or Python). Instructors: Arnold, Pierce.

ChE/Ch 164. Introduction to Statistical Thermodynamics. *9 units (3-0-6); second term. Prerequisite: Ch 21 abc or instructor's permission.* An introduction to the fundamentals and simple applications of statistical thermodynamics. Foundation of statistical mechanics; partition functions for various ensembles and their connection to thermodynamics; fluctuations; noninteracting quantum and classical gases; heat capacity of solids; adsorption; phase transitions and order parameters; linear response theory; structure of classical fluids; computer simulation methods. Instructors: Wang, Miller.

ChE/Ch 165. Chemical Thermodynamics. *9 units (3-0-6); first term. Prerequisite: ChE 63 ab or instructor's permission.* An advanced course emphasizing the conceptual structure of modern thermodynamics and its applications. Review of the laws of thermodynamics; thermodynamic potentials and Legendre transform; equilibrium and stability conditions; metastability and phase separation kinetics; thermodynamics of single-component fluid and binary mixtures; models for solutions; phase and chemical equilibria; surface and interface thermodynamics; electrolytes and polymeric liquids. Instructor: Wang.

ChE/BE 169. Biomolecular Cell Engineering. *9 units (3-0-6); first term. Prerequisites: ChE 101 or Ch 24 and Ch 25 or equivalent, ACM 95 b or concurrent registration.* Quantitative analysis of molecular mechanisms governing mammalian cell behavior. Topics include topology and dynamics of signaling and genetic regulatory networks, receptor-ligand trafficking, and biophysical models for cell adhesion and migration. Not offered 2010–11.

ChE 174. Special Topics in Transport Phenomena. *9 units (3-0-6); third term. Prerequisites: ACM 95/100 and ChE 151 ab or instructor's permission. May be repeated for credit.* Advanced problems in heat, mass, and momentum transfer. Introduction to mechanics of complex fluids; physicochemical hydrodynamics; microstructured fluids; colloidal dispersions; microfluidics; selected topics in hydrodynamic stability theory; transport phenomena in materials processing. Other topics may be discussed depending on class needs and interests. Instructor: Brady. Given in alternate years; not offered 2010–11.

ChE 280. Chemical Engineering Research. *Offered to Ph.D. candidates in chemical engineering.* Main lines of research now in progress are covered in detail in section two.

CHEMISTRY

Ch 1 ab. General Chemistry. *6 units (3-0-3) first term; 9 units (4-0-5) second term.* Lectures and recitations dealing with the principles of chemistry. First term: electronic structure of atoms, periodic properties, ionic substances, covalent bonding, Lewis representations of molecules and ions, shapes of molecules, Lewis acids and bases, Bronsted acids and bases, hybridization and resonance, bonding in solids. Second term: chemical equilibria, oxidation and reduction, thermodynamics, kinetics, introduction to organic chemistry and the chemistry of life. Graded pass/fail. Instructors: Lewis, Heath, Reisman.

Ch/APh 2. Introduction to Energy Sciences. *9 units (4-0-5); third term. Prerequisites: Ch 1 ab, Ph 1 ab, Ma 1 ab.* Energy production and transduction in biological, chemical, and nuclear reactions. Bioenergetics: energy sources and storage; components of biological energy flows: pumps, motors, and solar cells; circuitry of biological energy flows and biological energy transduction pathways. Chemistry of energy production and utilization: fossil fuel utilization and energy conversion pathways; artificial photosynthesis, solar cells, and solar energy conversion. Principles of nuclear energy production: nuclear energy decay processes, fission and fusion reactions, and reactor principles. Not offered on a pass/fail basis. Instructors: Lewis, Bellan, Arnold. *Satisfies the menu requirement of the Caltech core curriculum.*

Ch 3 a. Fundamental Techniques of Experimental Chemistry. *6 units (1-3-2); first, second, third terms.* Introduces the basic principles and techniques of synthesis and analysis and develops the laboratory skills and precision that are fundamental to experimental chemistry. Freshmen who have gained advanced placement into Ch 41 or Ch 21, or who are enrolled in Ch 10, are encouraged to take Ch 3 a in the fall term. Graded pass/fail. Instructor: Mendez.

Ch 3 b. Experimental Procedures of Synthetic Chemistry. *8 units (1-6-1); first, third terms. Prerequisites: Ch 1 ab and Ch 3 a.* Instruction in fundamental synthesis, separation, and characterization procedures used in chemical research. Enrollment in the spring term is limited, with priority given to chemical engineering majors. Instructor: Mendez.

Ch 3 x. Experimental Methods in Solar Energy Conversion. *6 units (1-3-2); first, second, third terms. Prerequisites: Ch 1 a or advanced placement into Ch 41 or Ch 21.* Introduces concepts and laboratory methods in chemistry and materials science centered on the theme of solar energy conversion and storage. Students will perform experiments involving optical spectroscopy, electrochemistry, laser spectroscopy, nanoparticle synthesis, photochemistry, and photoelectrochemistry, culminating in the construction and testing of dye-sensitized solar cells. A lecture component is included. Instructors: Winkler, Brunschwig.

Ch 4 ab. Synthesis and Analysis of Organic and Inorganic Compounds. *9 units (1-6-2). Prerequisites: Ch 1 (or the equivalent) and Ch 3 a.* Previous or concurrent enrollment in Ch 41 is strongly recommended. Introduction to methods of synthesis, separation, purification, and characterization used routinely in chemical research laboratories. Ch 4 a emphasizes spectroscopic methods of analysis; Ch 4 b stresses applications of chromatography in addition to more classical separation techniques. Ch 4 a, second term; Ch 4 b, third term only. Instructor: Mendez.

Ch 5 ab. Advanced Techniques of Synthesis and Analysis. *Ch 5 a 12 units (1-9-2), second term; Ch 5 b 9 units (1-6-2), first term. Prerequisite: Ch 4 ab. Ch 102 strongly recommended for Ch 5 b.* Modern synthetic chemistry. Specific experiments may change from year to year. Experiments illustrating the multistep syntheses of natural products (Ch 5 a), coordination complexes, and organometallic complexes (Ch 5 b) will be included. Methodology will include advanced techniques of synthesis and instrumental characterization. Terms may be taken independently. Instructors: Grubbs (a), Agapie (b).

Ch 6 ab. Physical and Biophysical Chemistry Laboratory. *10 units (1-6-3); second, third terms. Prerequisites: Ch 1, Ch 4 ab, and Ch 21 or Ch 24 or equivalents (may be taken concurrently).* Introduction to modern physical methods in chemistry and biology. Techniques include laser spectroscopy, microwave spectroscopy, electron spin resonance, nuclear magnetic resonance, mass spectrometry, FT-IR, fluorescence, X-ray diffraction, scanning probe microscopies, and UHV surface methods. The two terms can be taken in any order. Instructors: Beauchamp, Weitekamp.

Ch 7. Advanced Experimental Methods in Bioorganic Chemistry. *9 units (1-6-2); third term. Prerequisites: Ch 41 abc, and Bi/Ch 110, Ch 4 ab. Enrollment by instructor's permission. Preference will be given to students who have taken Ch 5 a or Bi 10.* This advanced laboratory course will provide experience in the powerful contemporary methods for polypeptide and oligonucleotide synthesis. Experiments will address nucleic acid and amino acid protecting group strategies, biopolymer assembly and isolation, and product characterization. A strong emphasis will be placed on understanding the chemical basis underlying the successful utilization of these procedures. In addition, experiments to demonstrate the application of commercially available enzymes for useful synthetic organic transformations will be illustrated. Instructor: Hsieh-Wilson.

Ch 10 abc. Frontiers in Chemistry. *3 units (2-0-1); first, second terms. 8 units (1-6-1); third term. Open for credit to freshmen and sophomores. Prerequisites: Ch 10 c prerequisites are Ch 10 ab, Ch 3 a, and either Ch 1 ab, Ch 41 ab, or Ch 21 ab, and instructor's permission.* Ch 10 ab is a weekly seminar by a member of the chemistry department on a topic of current research; the topic will be presented at an informal, introductory level. The other weekly session will acquaint students with the laboratory techniques and instrumentation used on the research topics. Ch 10 c is a research-oriented laboratory course, which will be supervised by a chemistry faculty member. Weekly class meetings will provide a forum for participants to discuss their research projects. Graded pass/fail. Instructors: Dervan, Peters.

Ch 14. Chemical Equilibrium and Analysis. *6 units (2-0-4); third term.* A systematic treatment of ionic equilibria in solution. Topics covered include acid-base equilibria in aqueous and nonaqueous solutions, complex ion formation, chelation, oxidation-reduction reactions, and some aspects of reaction mechanisms. Instructors: Richards, Shahgholi.

Ch 15. Chemical Equilibrium and Analysis Laboratory. *10 units (0-6-4); first term. Prerequisites: Ch 1 ab, Ch 3 a, Ch 14, or instructor's permission.* Laboratory experiments are used to illustrate modern instrumental techniques that are currently employed in industrial and academic research. Emphasis is on determinations of chemical composition, measurement of equilibrium constants, evaluation of rates of chemical reactions, and trace-metal analysis. Instructor: Dalleska.

Ch 21 abc. Physical Chemistry. *9 units (3-0-6); first, second, third terms. Prerequisites: Ch 1 ab, Ph 2 ab, Ma 2 ab.* Atomic and molecular quantum mechanics, spectroscopy, thermodynamics, statistical mechanics, and chemical kinetics. Instructors: Okumura, Blake, Miller.

Ch 24. Introduction to Biophysical Chemistry: Spectroscopy. *9 units (3-0-6); second term. Prerequisites: Ma 1 abc, Ph 1 abc, Ph 2 ab or Ph 12 a, and Ch 21 a or Ph 12 b.* Develops the basic principles of the interaction of light with matter, including spectroscopic and scattering methods of macromolecular structure determination, with emphasis on biochemical and biophysical applications. Instructor: Heath.

Ch 25. Introduction to Biophysical Chemistry: Thermodynamics. *9 units (3-0-6); third term. Prerequisites: Ma 1 abc, Ph 1 abc and Ph 2 ab; Ch 21 a and Ch 24 recommended.* Develops the basic principles of solution thermodynamics, transport processes, and reaction kinetics, with emphasis on biochemical and biophysical applications. Instructor: Rees.

Ch 41 abc. Organic Chemistry. *9 units (3-0-6); first, second, third terms. Prerequisite: Ch 1 ab or instructor's permission.* The synthesis, structures, and mechanisms of reactions of organic compounds. Instructors: Dougherty, Dervan, Stoltz.

Ch 80. Chemical Research. *Offered to B.S. candidates in chemistry. Units in accordance with work accomplished. Prerequisite: consent of research supervisor.* Experimental and theoretical research requiring a report containing an appropriate description of the research work.

Ch 81. Independent Reading in Chemistry. *Units by arrangement. Prerequisite: instructor's permission.* Occasional advanced work involving reading assignments and a report on special topics. No more than 12 units in Ch 81 may be used as electives in the chemistry option.

Ch 82. Senior Thesis Research. *9 units; first, second, third terms. Prerequisite: instructor's permission.* Three terms of Ch 82 are to be completed during the junior and/or senior year of study. At the end of the third term, a thesis of approximately 20 pages (excluding figures and references) will be presented to the mentor and the Chemistry Curriculum and Undergraduate Studies Committee. An oral thesis defense will be arranged by the CUSC. The thesis must be approved by both the research mentor and the CUSC. The first two terms of Ch 82 will be taken on a pass/fail basis, and the third term will carry a letter grade. Instructor: Rees.

Ch 90. Oral Presentation. *3 units (2-0-1); second term.* Training in the techniques of oral presentation of chemical and biochemical topics. Practice in the effective organization and delivery of technical reports before groups. Graded pass/fail. Instructors: Zewail, Bikle.

Ch/ChE 91. Scientific Writing. *3 units (2-0-1); first, second, third term.* Training in the writing of scientific research papers for chemists and chemical engineers. *Fulfills the Institute scientific writing requirement.* Instructors: Parker, Labinger, Flagan.

Ch 102. Introduction to Inorganic Chemistry. *9 units (3-0-6); third term. Prerequisite: Ch 41 ab.* Structure and bonding of inorganic species with special emphasis on spectroscopy, ligand substitution processes, oxidation-reduction reactions, and biological inorganic chemistry. Letter grades only. Instructor: Agapie.

Bi/Ch 110. Introduction to Biochemistry. *12 units (4-0-8).* For course description, see Biology.

Bi/Ch 111. Biochemistry of Gene Expression. *12 units (4-0-8).* For course description, see Biology.

Ch 112. Inorganic Chemistry. *9 units (3-0-6); first term. Prerequisite: Ch 102 or instructor's permission.* Introduction to group theory, ligand field theory, and bonding in coordination complexes and organotransition metal compounds. Systematics of synthesis, bonding, and reactivities of commonly encountered classes of transition metal compounds. Instructor: Bercaw.

Bi/Ch 113. Biochemistry of the Cell. *12 units (4-0-8)*. For course description, see Biology.

Ch 117. Introduction to Electrochemistry. *9 units (3-0-6); second term.* Discussion of the structure of electrode-electrolyte interface, the mechanism by which charge is transferred across it, and experimental techniques used to study electrode reactions. Topics change from year to year but usually include diffusion currents, polarography, coulometry, irreversible electrode reactions, the electrical double layer, and kinetics of electrode processes. Instructor: Lewis.

Ch 120 ab. Nature of the Chemical Bond. *9 units (3-0-6) first, (1-1-7) third terms. Prerequisite: general exposure to quantum mechanics (e.g., Ch 21 a).* Modern ideas of chemical bonding, with an emphasis on qualitative concepts useful for predictions of structures, energetics, excited states, and properties. Part a: The quantum mechanical basis for understanding bonding, structures, energetics, and properties of materials (polymers, ceramics, metals alloys, semiconductors, and surfaces), including transition metal and organometallic systems with a focus on chemical reactivity. The emphasis is on explaining chemical, mechanical, electrical, and thermal properties of materials in terms of atomistic concepts. Part b: The student does an individual research project using modern quantum chemistry computer programs to calculate wavefunctions, structures, and properties of real molecules. Instructor: Goddard.

Ch 121 ab. Atomic-Level Simulations of Materials and Molecules. *Ch 121 a: 9 units (3-0-6) third term; Ch 121 b (1-1-7) first term. Prerequisite: Ch 21 a or Ch 125 a.* Atomistic-based methods for predicting the structures and properties of molecules and solids and simulating the dynamical properties. The course will highlight theoretical foundations and applications of atomistic simulations to current problems in such areas as biological systems (proteins, DNA, carbohydrates, lipids); polymers (crystals, amorphous systems, copolymers); semiconductors (group IV, III-V, surfaces, defects); inorganic systems (ceramics, zeolites, superconductors, and metals); organometallics, and catalysis (heterogeneous and homogeneous). Part a covers the basic methods with hands-on applications to systems of interest using modern software. All homework and exams emphasize computer-based solutions. Part b: each student selects a research project and uses atomistic simulations to solve it. Instructor: Goddard.

Ch 122. Structure Determination by X-ray Crystallography. *9 units (3-0-6); first term. Prerequisite: Ch 21 abc or instructor's permission.* Methods for solving the crystal structures of organic and inorganic molecules, peptides, nucleic acids, and proteins. Topics include symmetry, space groups, diffraction by crystals, the direct and reciprocal lattice, powder diffraction, Patterson and direct methods for phase determination, isomorphous replacement phasing for macromolecules, and structure refinement. Instructor: Day.

Ch 125 abc. The Elements of Quantum Chemistry. *9 units (3-0-6); first, second terms. Prerequisite: Ch 21 abc or an equivalent brief introduction to quantum mechanics.* A first course in molecular quantum mechanics consisting of a quantitative treatment of quantum mechanics with applications to systems of interest to chemists. The basic elements of quantum mechanics, the electronic structure of atoms and molecules, the interactions of radiation fields and matter, scattering theory, and reaction rate theory. Instructors: Weitekamp, McKoy.

Ch 126. Molecular Spectra and Molecular Structure. *9 units (3-0-6); third term. Prerequisite: Ch 21 and Ch 125 a taken concurrently, or instructor's permission.* Quantum mechanical foundations of the spectroscopy of molecules. Topics include quantum theory of angular momentum, rovibrational Hamiltonian for polyatomic molecules, molecular symmetry and permutation-inversion groups, electronic spectroscopy, interaction of radiation and matter. Not offered 2010–11.

Ge/Ch 127. Nuclear Chemistry. *9 units (3-0-6).* For course description, see Geological and Planetary Sciences.

Ge/Ch 128. Cosmochemistry. *9 units (3-0-6).* For course description, see Geological and Planetary Sciences.

Bi/Ch 132. Biophysics of Macromolecules. *9 units (3-0-6).* For course description, see Biology.

Ch 135 ab. Chemical Dynamics. *9 units (3-0-6); part a, second term; part b, third term. Prerequisites: Ch 21 abc and Ch 41 abc, or equivalent, or instructor's permission.* Part a: introduction to the dynamics of chemical reactions. Topics include scattering cross sections, rate constants, intermolecular potentials, reactive scattering, nonadiabatic processes, statistical theories of unimolecular reactions, and the application of laser and molecular beam techniques to the study of reaction mechanisms. Part b: the quantum description of chemical reactions. The scattering matrix. The calculation of reaction cross sections, probabilities, and rate constants. Collision lifetimes and resonances. Classical trajectories. The two terms can be taken independently. Instructor: Marcus. Part b not offered 2010–11.

Ch/ChE 140 ab. Principles and Applications of Semiconductor Photoelectrochemistry. *9 units (3-0-6); second, third terms. Prerequisite: APh/EE 9 ab or instructor's permission.* The properties and photoelectrochemistry of semiconductors and semiconductor/liquid junction solar cells will be discussed. Topics include optical and electronic properties of semiconductors; electronic properties of semiconductor junctions with metals, liquids, and other semiconductors, in the dark and under illumination, with emphasis on semiconductor/liquid junctions in aqueous and nonaqueous media. Problems currently facing semiconductor/

liquid junctions and practical applications of these systems will be highlighted. Not offered 2010–11.

Ch 143. Basic FT NMR Spectroscopy. *9 units (3-2-4); second term. Prerequisite: Ch 41 abc.* The course will cover NMR basics and applications, with emphasis on FT NMR and the principles of multipulse NMR techniques used in structural analysis, including determination of relaxation times, INEPT, DEPT, NOSEY, and COSY. A number of NMR techniques will be illustrated with the Chapman-Russell *FT NMR Problems* videodisc-based computer program, which features on-screen spectra at a variety of magnetic fields with, and without, decoupling, 2-D spectra, and so on. The practical use of NMR will be further demonstrated by laboratory exercises using modern pulse FT NMR techniques with high-field spectrometers for structural analysis. Not offered 2010–11.

Ch 144 ab. Advanced Organic Chemistry. *9 units (3-0-6); first, second terms. Prerequisite: Ch 41 abc; Ch 21 abc recommended.* An advanced survey of selected topics in modern physical organic chemistry. Topics vary from year to year and may include structural and theoretical organic chemistry; molecular recognition/supramolecular chemistry; reaction mechanisms and the tools to study them; reactive intermediates; materials chemistry; pericyclic reactions; and photochemistry. Not offered 2010–11.

Ch 145. Bioorganic Chemistry of Proteins. *9 units (3-0-6); first term. Prerequisite: Ch 41 abc; Bi/Ch 110 recommended.* An advanced survey of current and classic topics in bioorganic chemistry/chemical biology. The content will vary from year to year and may include the structure, function, and synthesis of peptides and proteins; enzyme catalysis and inhibition; carbohydrates and glycobiology; chemical genetics; genomics and proteomics; posttranslational modifications; chemical tools to study cellular dynamics; and enzyme evolution. Instructor: Hsieh-Wilson.

Ch 146. Bioorganic Chemistry of Nucleic Acids. *9 units (3-0-6); third term. Prerequisite: Ch 41 ab.* The course will examine the bioorganic chemistry of nucleic acids, including DNA and RNA structures, molecular recognition, and mechanistic analyses of covalent modification of nucleic acids. Topics include synthetic methods for the construction of DNA and RNA; separation techniques; recognition of duplex DNA by peptide analogs, proteins, and oligonucleotide-directed triple helical formation; RNA structure and RNA as catalysts (ribozymes). Not offered 2010–11.

Ch/ChE 147. Polymer Chemistry. *9 units (3-0-6); second term. Prerequisite: Ch 41 abc.* An introduction to the chemistry of polymers, including synthetic methods, mechanisms and kinetics of macromolecule formation, and characterization techniques. Not offered 2010–11.

ChE/Ch 148. Polymer Physics. *9 units (3-0-6).* For course description, see Chemical Engineering.

Ch 153 ab. Advanced Inorganic Chemistry. *9 units (3-0-6); second, third terms. Prerequisites: Ch 112 and Ch 21 abc or concurrent registration.* Ch 153 a: Topics in modern inorganic chemistry. Electronic structure, spectroscopy, and photochemistry with emphasis on examples from the modern research literature. Ch 153 b: Applications of physical methods toward the characterization of inorganic and bioinorganic species. A range of spectroscopic approaches will be covered. Instructors: Gray, Winkler (a); Peters (b).

Ch 154 ab. Organometallic Chemistry. *9 units (3-0-6); second, third terms. Prerequisite: Ch 112 or equivalent.* A general discussion of the reaction mechanisms and the synthetic and catalytic uses of transition metal organometallic compounds. Second term: a survey of the elementary reactions and methods for investigating reaction mechanisms. Third term: contemporary topics in inorganic and organometallic synthesis, structure and bonding, and applications in catalysis. Instructors: Labinger, Bercaw. Part b not offered 2010–11.

ChE/Ch 155. Chemistry of Catalysis. *9 units (3-0-6).* For course description, see Chemical Engineering.

ChE/Ch 164. Introduction to Statistical Thermodynamics. *9 units (3-0-6).* For course description, see Chemical Engineering.

ChE/Ch 165. Chemical Thermodynamics. *9 units (3-0-6).* For course description, see Chemical Engineering.

Ch 166. Nonequilibrium Statistical Mechanics. *9 units (3-0-6); third term. Prerequisite: Ch 21 abc or equivalent.* Transport processes in dilute gases; Boltzmann equation; Brownian motion; Langevin and Fokker-Planck equations; linear response theory; time-correlation functions and applications; nonequilibrium thermodynamics. Instructor: Marcus.

BMB/Bi/Ch 170 abc. Biochemistry and Biophysics of Macromolecules and Molecular Assemblies. *9 units (3-1-5).* For course description, see Biochemistry and Molecular Biophysics.

ESE/Ge/Ch 171. Atmospheric Chemistry I. *9 units (3-0-6).* For course description, see Environmental Science and Engineering.

ESE/Ge/Ch 172. Atmospheric Chemistry II. *3 units (3-0-0).* For course description, see Environmental Science and Engineering.

ESE/Ch/Ge 175 ab. Environmental Organic Chemistry. *9 units (3-0-6).* For course description, see Environmental Science and Engineering.

BMB/Ch 178. Enzyme Kinetics and Mechanisms. *9 units (3-0-6).* For course description, see Biochemistry and Molecular Biophysics.

Ch 180. Chemical Research. *Units by arrangement. Offered to M.S. candidates in chemistry.* Graded pass/fail.

BMB/Ch 202 abc. Biochemistry Seminar Course. *1 unit.* For course description, see Biochemistry and Molecular Biophysics.

Ch 212. Bioinorganic Chemistry. *9 units (3-0-6); third term. Prerequisites: Ch 112 and Bi/Ch 110 or equivalent.* Current topics in bioinorganic chemistry will be discussed, including metal storage and regulation, metalloenzyme structure and reactions, biological electron transfer, metalloprotein design, and metal-nucleic acid interactions and reactions. Not offered 2010–11.

Ch 213 abc. Advanced Ligand Field Theory. *12 units (1-0-11); first, second, third terms. Prerequisite: Ch 21 abc or concurrent registration.* A tutorial course of problem solving in the more advanced aspects of ligand field theory. Recommended only for students interested in detailed theoretical work in the inorganic field. Instructors: Gray, staff.

Ch 224. Advanced Topics in Magnetic Resonance. *9 units (2-0-7); third term. Prerequisite: Ch 125 abc or Ph 125 abc or concurrent registration or equivalent; Ch 122 b or equivalent.* A detailed presentation of some of the important concepts in magnetic resonance unified by the spin density operator formalism. Topics will include both classic phenomena and recent development, especially in solid-state and two-dimensional NMR. Not offered 2010–11.

Ch 227 ab. Advanced Topics in Chemical Physics. *9 units (3-0-6); part a second term; part b third term. Prerequisite: Ch 125 abc or Ph 125 abc or equivalent.* The general quantum mechanical theory of molecular collisions will be presented in detail. Quasi-classical, semi-classical, and other approximations. Applications to inelastic and reactive molecule-molecule and inelastic electron-molecule collisions. Not offered 2010–11.

Ch 228. Dynamics and Complexity in Physical and Life Sciences. *9 units (3-0-6); third term.* This course is concerned with the dynamics of molecular systems, with particular focus on complexity, the elementary motions that lead to functions in chemical and biological assemblies. It will address principles of dynamics as they relate to the nature of the chemical bond. An overview of modern techniques, such as those involving lasers, NMR, and diffraction, for unraveling dynamics in complex systems. Applications from areas of physics, chemistry, and biology—from coherence and chaos to molecular recognition and self-assembly. Instructor: Zewail.

Ch/Bi 231. Advanced Topics in Biochemistry. *6 units (2-0-4); third term.* Transcriptional regulation in eukaryotes. Topics: the subunit structure of eukaryotic RNA polymerases and their role in transcriptional reactions; the composition of eukaryotic promoters, including regulatory units; general and specific transcription factors; developmental regulatory circuits and factors; structural motifs involved in DNA binding and transcriptional initiation and control. Instructors: Parker, Campbell.

Ch 242 ab. Chemical Synthesis. *9 units (3-0-6); first, second terms. Prerequisite: Ch 41 abc.* An integrated approach to synthetic problem solving featuring an extensive review of modern synthetic reactions with concurrent development of strategies for synthesis design. Part a will focus on the application of modern methods of stereocontrol in the construction of stereochemically complex acyclic systems. Part b will focus on strategies and reactions for the synthesis of cyclic systems. Instructors: Reisman, Virgil.

Ch 247. Organic Reaction Mechanisms. *6 units (2-0-4); third term.* A mechanistic view of free-radical reactions using examples from biological systems. Topics: initiation, termination, and propagation of radical reactions in vivo, mechanisms of lipid damage, spin labeling, photosynthesis, oxygen radicals and oxygen toxicity, and radical reactions in proteins and nucleic acids. Not offered 2010–11.

Ch 250. Advanced Topics in Chemistry. *Units and term to be arranged.* Content will vary from year to year; topics are chosen according to interests of students and staff. Visiting faculty may present portions of this course. Instructors: Grubbs, Stoltz, Reisman.

Ch 280. Chemical Research. *Hours and units by arrangement.* By arrangement with members of the faculty, properly qualified graduate students are directed in research in chemistry.

CIVIL ENGINEERING

CE 90 abc. Structural Analysis and Design. *9 units (3-0-6); first, second, third terms. Prerequisite: ME 35 abc.* Structural loads; influence lines for statically determinate beams and trusses; deflection of beams; moment area and conjugate beam theorems; approximate methods of analysis of indeterminate structures; slope deflection and moment distribution techniques. Generalized stiffness and flexibility analyses of indeterminate structures. Design of selected structures in timber, steel, and reinforced concrete providing an introduction to working stress, load and resistance factor, and ultimate strength approaches. In each of the second and third terms a design project will be undertaken involving consideration of initial conception, cost-benefit, and optimization aspects of a constructed facility. Not offered 2010–11.

CE 100. Special Topics in Civil Engineering. *Units to be based upon work done, any term.* Special problems or courses arranged to meet the needs of first-year graduate students or qualified undergraduate students. Graded pass/fail.

Ae/APh/CE/ME 101 abc. Fluid Mechanics. *9 units (3-0-6).* For course description, see Aerospace.

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

CE/Ae/AM 108 abc. Computational Mechanics. *9 units (3-0-6); first, second, third terms. Prerequisite: instructor's permission.* Numerical analysis by the finite element method covering fundamental concepts and computer implementation. Solution of systems of linear equations and eigenvalue problems. Solution of the partial differential equations of heat transfer, solid and structural mechanics, and fluid mechanics. Transient and nonlinear problems. Instructor: Staff.

CE 130 abc. Civil Engineering Seminar. *1 unit; each term.* All candidates for the M.S. degree in civil engineering are required to attend a graduate seminar, in any division, each week of each term. Students not registered for the M.S. degree in civil engineering must receive the instructor's permission. Graded pass/fail. Instructor: Staff.

AM/CE 151 ab. Dynamics and Vibrations. *9 units (3-0-6).* For course description, see Applied Mechanics.

CE 160 ab. Structural and Earthquake Engineering. *9 units (3-0-6); second, third terms.* Matrix structural analysis of the static and dynamic response of structural systems, Newmark time integration, Newton-Raphson iteration methodology for the response of nonlinear systems, stability of iteration schemes, static and dynamic numerical analysis of planar beam structures (topics include the development of stiffness, mass, and damping matrices, material and geometric nonlinearity effects, formulation of a nonlinear 2-D beam element, uniform and nonuniform earthquake loading, soil-structure interaction, 3-D beam element formulation, shear deformations, and panel zone deformations in steel frames, and large deformation analysis), seismic design and analysis of steel moment frame and braced frame systems, steel member behavior (topics include bending, buckling, torsion, warping, and lateral torsional buckling, and the effects of residual stresses), reinforced concrete member behavior (topics include bending, shear, torsion, and PMM interaction), and seismic design requirements for reinforced concrete structures. Not offered 2010–11.

Ae/CE 165 ab. Mechanics of Composite Materials and Structures. *9 units (2-2-5).* For course description, see Aerospace.

CE 180. Experimental Methods in Earthquake Engineering. *9 units (1-5-3); third term. Prerequisite: AM/CE 151 abc or equivalent.* Laboratory work involving calibration and performance of basic transducers suitable for the measurement of strong earthquake ground motion, and of structural response to such motion. Study of principal methods of dynamic tests of structures, including generation of forces and measurement of structural response. Instructor: Kohler.

CE 181 ab. Engineering Seismology. *9 units (3-0-6); second, third terms.* Characteristics of potentially destructive earthquakes from the engineering point of view. Theory of seismometers, seismic waves in a continuum, plane waves in layered media, surface waves, basin waves, site effects, dynamic deformation of buildings, seismic sources, earthquake size scaling, earthquake hazard calculations, rupture dynamics. Instructor: Heaton.

CE 200. Advanced Work in Civil Engineering. *6 or more units as arranged; any term.* Members of the staff will arrange special courses on advanced topics in civil engineering for properly qualified graduate students. The following numbers may be used to indicate a particular area of study.

Ae/AM/CE/ME 214 abc. Computational Solid Mechanics. *9 units (3-0-6).* For course description, see Aerospace.

Ae/CE 221. Space Structures. *9 units (3-0-6).* For course description, see Aerospace.

Ge/ESE/CE 226. Sediment Transport Mechanics and Morphodynamics. *9 units (3-0-6).* For course description, see Geological and Planetary Sciences.

CE 300. Research in Civil Engineering. *Hours and units by arrangement.* Research in the field of civil engineering. By arrangements with members of the staff, properly qualified graduate students are directed in research.

COMPUTATION AND NEURAL SYSTEMS

CNS 100. Introduction to Computation and Neural Systems. *1 unit; first term.* This course is designed to introduce undergraduate and first-year CNS graduate students to the wide variety of research being undertaken by CNS faculty. Topics from all the CNS research labs are discussed and span the range from biology to engineering. Graded pass/fail. Instructor: Koch.

CNS/SS/Psy/Bi 102 ab. Brains, Minds, and Society. *9 units (3-0-6); second, third terms. Prerequisites: Bi/CNS 150 and CNS/Bi/Ph/CS 187, or instructor's permission.* Introduction to the computations made by the brain during economic and social decision making and their neural substrates. First quarter: Signal detection theory. Unconscious and conscious processing. Emotion and the somatic marker hypothesis. Perceptual decision making. Reinforcement learning. Goal and habit learning. Facial processing in social neuroscience. Second quarter: Optimal Bayesian decision making and prospect theory. Standard and behavioral game theory. Evolution and group decision making. Collective decision making by animals. Exploration. Risk learning. Probabilistic sophistication. Instructors: Adolphs, Bossaerts, Camerer, Koch, Rangel, O'Doherty.

CNS/SS/Psy 110 abc. Cognitive Neuroscience Tools. *5 units (1.5-0-3.5).* This course covers tools and statistical methods used in cognitive neuroscience research. Topics vary from year to year depending on the interests of the students. Recent topics include statistical modeling for fMRI data, experimental design for fMRI, and the preprocessing of fMRI data. Instructor: Rangel.

CNS/Bi/Psy 120. The Neuronal Basis of Consciousness. *9 units (4-0-5); third term.* What are the correlates of consciousness in the brain? The course provides a framework for beginning to address this question using a reductionist point of view. It focuses on the neurophysiology of the primate visual system, but also discusses alternative approaches more suitable for work with rodents. Topics to be covered include the anatomy and physiology of the primate's visual system (striate and extrastriate cortical areas, dorsal/ventral distinction, visual-frontal connections), iconic and working memory, selective visual attention, visual illusions, clinical studies (neglect, blind sight, split-brain, agnosia), direct stimulation of the brain, delay and trace associative conditioning, conscious and unconscious olfactory processing, and philosophical approaches to consciousness. Instructor: Koch.

Psy/CNS 130. Introduction to Human Memory. *9 units (3-0-6).* For course description, see Psychology.

CNS/Psy/Bi 131. The Psychology of Learning and Motivation. *9 units (3-0-6); second term.* This course will serve as an introduction to basic concepts, findings, and theory from the field of behavioral psychology, covering areas such as principles of classical conditioning, blocking and conditioned inhibition, models of classical conditioning, instrumental conditioning, reinforcement schedules, punishment and avoidance learning. The course will track the development of ideas from the beginnings of behavioral psychology in the early 20th century to contemporary learning theory. Not offered 2010–11.

EE/CNS/CS 148 ab. Selected Topics in Computational Vision. *9 units (3-0-6).* For course description, see Electrical Engineering.

Bi/CNS 150. Introduction to Neuroscience. *10 units (4-0-6).* For course description, see Biology.

CS/CNS/EE 154. Artificial Intelligence. *9 units (3-3-3).* For course description, see Computer Science.

CS/CNS/EE 155. Probabilistic Graphical Models. *9 units (3-3-3).* For course description, see Computer Science.

CS/CNS/EE 156 ab. Learning Systems. *9 units (3-0-6).* For course description, see Computer Science.

Bi/CNS 157. Comparative Nervous Systems. *9 units (2-3-4).* For course description, see Biology.

Bi/CNS 158. Vertebrate Evolution. *9 units (3-0-6).* For course description, see Biology.

CS/CNS/EE 159. Projects in Machine Learning and AI. *9 units (0-0-9).* For course description, see Computer Science.

Bi/CNS 162. Cellular and Systems Neuroscience Laboratory. *12 units (2-7-3).* For course description, see Biology.

CS/CNS 171. Introduction to Computer Graphics Laboratory. *12 units (3-6-3).* For course description, see Computer Science.

CS/CNS 174. Computer Graphics Projects. *12 units (3-6-3).* For course description, see Computer Science.

CNS/Bi/SS/Psy 176. Cognition. *12 units (6-0-6); third term.* The cornerstone of current progress in understanding the mind, the brain, and the relationship between the two is the study of human and animal cognition. This course will provide an in-depth survey and analysis of behavioral observations, theoretical accounts, computational models, patient data, electrophysiological studies, and brain-imaging results on mental capacities such as attention, memory, emotion, object representation, language, and cognitive development. Instructor: Shimojo.

CNS 180. Research in Computation and Neural Systems. *Units by arrangement with faculty. Offered to precandidacy students.*

Bi/CNS 184. The Primate Visual System. *9 units (3-1-5).* For course description, see Biology.

CNS/Bi/EE 186. Vision: From Computational Theory to Neuronal Mechanisms. *12 units (4-4-4); second term.* Lecture, laboratory, and project course aimed at understanding visual information processing, in both machines and the mammalian visual system. The course will emphasize an interdisciplinary approach aimed at understanding vision at several levels: computational theory, algorithms, psychophysics, and hardware (i.e., neuroanatomy and neurophysiology of the mammalian visual system). The course will focus on early vision processes, in particular motion analysis, binocular stereo, brightness, color and texture analysis, visual attention and boundary detection. Students will be required to hand in approximately three homework assignments as well as complete one project integrating aspects of mathematical analysis, modeling, physiology, psychophysics, and engineering. Instructors: Perona, Shimojo, Koch. Given in alternate years; not offered 2010–11.

CNS/Bi/Ph/CS 187. Neural Computation. *9 units (3-0-6); first term. Prerequisites: familiarity with digital circuits, probability theory, linear algebra, and differential equations. Programming will be required.* This course investigates computation by neurons. Of primary concern are models of neural computation and their neurological substrate, as well as the physics of collective computation. Thus, neurobiology is used as a motivating factor to introduce the relevant algorithms. Topics include rate-code neural networks, their differential equations, and equivalent circuits; stochastic models and their energy functions; associative memory; supervised and unsupervised learning; development; spike-based computing; single-cell computation; error and noise tolerance. Instructor: Perona.

CNS/CS/EE 188. Topics in Computation and Biological Systems. *9 units (3-0-6); second term. Prerequisite: Ma 2 or IST 4.* Advanced topics related to computational methods in biology. Topics might change from year to year. Examples include spectral analysis techniques and their applications in threshold circuits complexity and in computational learning theory. The role of feedback in computation. The logic of computation in gene regulation networks. The class includes a project that has the goal of learning how to understand, criticize, and present the ideas and results in research papers. Not offered 2010–11.

BE/CS/CNS/Bi 191 ab. Biomolecular Computation. *9 units.* For course description, see Bioengineering.

Bi/CNS 216. Behavior of Mammals. *6 units (2-0-4).* For course description, see Biology.

Bi/CNS 217. Central Mechanisms in Perception. *6 units (2-0-4).* For course description, see Biology.

Bi/CNS 220. Genetic Dissection of Neural Circuit Function. *6 units (2-0-4).* For course description, see Biology.

CNS/Bi 221. Computational Neuroscience. *9 units (4-0-5); third term. Prerequisite: Bi/CNS 150 or instructor's permission.* Lecture and discussion aimed at understanding computational aspects of information processing within the nervous system. The course will emphasize single neurons and how their biophysical properties relate to neuronal coding, i.e., how information is actually represented in the brain at the level of action potentials. Topics include biophysics of single neurons, signal detection and signal reconstruction, information theory, population coding and temporal coding in sensory systems of invertebrates and in the primate cortex. Students are required to hand in three homework assignments, discuss one set of papers in class, and participate in the debates. Not offered 2010–11.

CNS/Bi 247. Cerebral Cortex. *6 units (2-0-4); second term. Prerequisite: Bi/CNS 150 or equivalent.* A general survey of the structure and function of the cerebral cortex. Topics include cortical anatomy, functional localization, and newer computational approaches to understanding cortical processing operations. Motor cortex, sensory cortex (visual, auditory, and somatosensory cortex), association cortex, and limbic cortex. Emphasis is on using animal models to understand human cortical function and includes correlations between animal studies and human neuropsychological and functional imaging literature. Instructor: Andersen. Given in alternate years; offered 2010–11.

BE/CNS 248. Magnetic Resonance Imaging. *9 units (3-1-5).* For course description, see Bioengineering.

Bi/CNS 250 b. Topics in Systems Neuroscience. *9 units (3-0-6).* For course description, see Biology.

CNS/SS 251. Human Brain Mapping: Theory and Practice. *9 units (2-1-6); second term.* A course in functional brain imaging. An overview of contemporary brain imaging techniques, usefulness of brain imaging compared to other techniques available to the modern neuroscientist. Review of what is known about the physical and biological bases of the signals being measured. Design and implementation of a brain imaging experiment and analysis of data (with a particular emphasis on fMRI). Instructor: O'Doherty.

CS/CNS/EE 253. Special Topics in Machine Learning. *9 units (3-3-3).* For course description, see Computer Science.

SS/Psy/Bi/CNS 255. Topics in Emotion and Social Cognition. *9 units (3-0-6).* For course description, see Social Science.

CNS/Bi 256. Decision Making. *6 units (2-0-4); third term.* This special topics course will examine the neural mechanisms of reward, decision making, and reward-based learning. The course covers the anatomy and physiology of reward and action systems. Special emphasis will be placed on the representation of reward expectation; the interplay between reward, motivation, and attention; and the selection of actions. Links between concepts in economics and the neural mechanisms of decision making will be explored. Data from animal and human studies collected using behavioral, neurophysiological, and functional magnetic resonance techniques will be reviewed. Instructor Andersen.

CNS 280. Research in Computation and Neural Systems. *Hours and units by arrangement. For graduate students admitted to candidacy in computation and neural systems.*

CNS/Bi 286 abc. Special Topics in Computation and Neural Systems. *Units to be arranged. First, second, third terms.* Students may register with permission of the responsible faculty member.

CS 1. Introduction to Computer Programming. *9 units (3-4-2); first term.* A course on computer programming emphasizing the program design process and pragmatic programming skills. It will use the Python programming language and will not assume previous programming experience. Material covered will include data types, variables, assignment, control structures, functions, scoping, compound data, string processing, modules, basic input/output (terminal and file), as well as more advanced topics such as recursion, exception handling and object-oriented programming. Program development and maintenance skills including debugging, testing, and documentation will also be taught. Assignments will include problems drawn from fields such as graphics, numerics, networking, and games. At the end of the course, students will be ready to learn other programming languages in courses such as CS 11, and will also be ready to take more in-depth courses such as CS 2 and CS 4. Instructor: Vanier.

CS 2. Introduction to Programming Methods. *9 units (2-4-3); second term. Prerequisite: CS 1 or equivalent.* CS 2 is a challenging course in programming languages and computer science, emphasizing modes of algorithmic expression. The course will include such topics as performance analysis of algorithms; proofs of program correctness; recursive and higher-order procedures; data structures, including lists, trees, graphs, and arrays; objects and abstract data types. The course includes weekly laboratory exercises and written homework covering the lecture material and program design. Instructor: Barr.

CS 3. Introduction to Software Engineering. *9 units (2-4-3); third term. Prerequisite: CS 2 or equivalent.* CS 3 is an advanced introduction to the fundamentals of computer science and software engineering methodology. Topics will be chosen from the following: abstract data types; object-oriented models and methods; logic, specification, and program composition; abstract models of computation; probabilistic algorithms; nondeterminism; distributed algorithms and data structures. The weekly laboratory exercises allow the students to investigate the lecture material by writing nontrivial applications. Instructor: Staff.

CS 4. Fundamentals of Computer Programming. *9 units (3-4-2); second term. Prerequisite: CS 1 or instructor's permission.* This course gives students the conceptual background necessary to construct and analyze programs, which includes specifying computations, understanding evaluation models, and using major programming language constructs (functions and procedures, conditionals, recursion and looping, scoping and environments, compound data, side effects, higher-order functions and functional programming, and object-oriented programming). It emphasizes key issues that arise in programming and in computation in general, including time and space complexity, choice of data representation, and abstraction management. This course is intended for students with some programming background who want a deeper understanding of the conceptual issues involved in computer programming. Instructor: Vanier.

Ma/CS 6 abc. Introduction to Discrete Mathematics. *9 units (3-0-6).* For course description, see Mathematics.

CS 9. Introduction to Computer Science Research. *1 unit (1-0-0); first term.* This course will introduce the research areas of the computer science faculty, through weekly overview talks by the faculty aimed at first-year undergraduates. Others may wish to take the course to gain an understanding of the scope of the field. Graded pass/fail. Instructor: Umans.

CS 11. Computer Language Shop. *3 units (0-3-0); first, second, third terms. Prerequisite: CS 1 or instructor's permission.* A self-paced lab that provides students with extra practice and supervision in transferring their programming skills to a particular programming language; the course can be used for any language of the student's choosing, subject to approval by the instructor. A series of exercises guide the student through the pragmatic use of the chosen language, building his or her familiarity, experience, and style. More advanced students may propose their own programming project as the target demonstration of their new language skills. CS 11 may be repeated for credit of up to a total of nine units. Instructors: Vanier, Pinkston.

CS 21. Decidability and Tractability. *9 units (3-0-6); second term. Prerequisite: CS 2 (may be taken concurrently).* This course introduces the formal foundations of computer science, the fundamental limits of computation, and the limits of efficient computation. Topics will include automata and Turing machines, decidability and undecidability, reductions between computational problems, and the theory of NP-completeness. Instructor: Umans.

CS 24. Introduction to Computing Systems. *9 units (3-3-3); third term. Prerequisites: CS 2 and CS 21; background in compiled languages such as C or C++ strongly recommended.* Basic introduction to computer systems, including hardware-software interface, computer architecture, and operating systems. Course emphasizes computer system abstractions and the hardware and software techniques necessary to support them, including virtualization (e.g., memory, processing, communication), dynamic resource management, and common-case optimization, isolation, and naming. Instructor: Pinkston.

CS 38. Introduction to Algorithms. *9 units (3-0-6); third term. Prerequisites: CS 2; Ma/CS 6 a or Ma 121 a; and CS 21 or CS/EE/Ma 129 a.* This course introduces techniques for the design and analysis of efficient algorithms. Major design techniques (the greedy approach, divide and conquer, dynamic programming, linear programming) will be introduced through a variety of algebraic, graph, and optimization problems. Methods for identifying intractability (via NP-completeness) will be discussed. Instructor: Kitaev.

CS 42. Introduction to Relational Databases. *9 units (3-0-6); second term. Prerequisite: CS 1 or equivalent.* Introduction to the basic theory and usage of relational database systems. It covers the relational data model, relational algebra, and the Structured Query Language (SQL). The course introduces the basics of database schema design and covers the entity-relationship model, functional dependency analysis, and normal forms. Additional topics include other query languages based on the relational calculi, data-warehousing and dimensional analysis, writing and using stored procedures, working with hierarchies and graphs within relational databases, and an overview of transaction processing and query evaluation. Extensive hands-on work with SQL databases. Not offered 2010–11.

EE/CS 51. Principles of Microprocessor Systems. *12 units (4-5-3).* For course description, see Electrical Engineering.

EE/CS 52. Microprocessor Systems Laboratory. *12 units (1-11-0).* For course description, see Electrical Engineering.

EE/CS 53. Microprocessor Project Laboratory. *12 units (0-12-0).* For course description, see Electrical Engineering.

CS/EE/ME 75 abc. Introduction to Multidisciplinary Systems Engineering. *3 units (2-0-1) , 6 units (2-0-4), or 9 units (2-0-7) first term; 6 units (2-3-1), 9 units (2-6-1), or 12 units (2-9-1) second term; 12 units (2-9-1), 15 units (2-12-1), or 18 units (2-15-1), with instructor's permission, third term.* This course presents the fundamentals of modern multidisciplinary systems engineering in the context of a substantial design project. Students from a variety of disciplines will conceive, design, implement, and operate a system involving electrical, information, and mechanical engineering components. Specific tools will be provided for setting project goals and objectives, managing interfaces between component subsystems, working in design teams, and tracking progress against tasks. Students will be expected to apply knowledge from other courses at Caltech in designing and implementing specific subsystems. During the first two terms of the course, students will attend project meetings and learn some basic tools for project design, while taking courses in CS, EE, and ME that are related to the course project. During the third term, the entire team will build, document, and demonstrate the course design project, which will differ from year to year. Freshmen must receive permission from the lead instructor to enroll. Instructors: Murray, Atwater, Hunt.

CS 80 abc. Undergraduate Thesis. *9 units; first, second, third terms. Prerequisite: instructor's permission, which should be obtained sufficiently early to allow time for planning the research.* Individual research project, carried out under the supervision of a member of the computer science faculty (or other faculty as approved by the computer science undergraduate option representative). Projects must include significant design effort. Written report required. Open only to upperclass students. Not offered on a pass/fail basis. Instructor: Staff.

CS 81 abc. Undergraduate Laboratory in Computer Science. *Units in accordance with work accomplished. Consent of both research adviser and course supervisor required before registering.* Supervised experimental research in computer science by undergraduates. Topic must be approved by the supervisor, and a formal final report must be presented on completion of research. Graded pass/fail. Instructor: Staff.

CS 90. Undergraduate Research in Computer Science. *Units in accordance with work accomplished. Consent of both research adviser and course supervisor required before registering.* Supervised research in computer science by undergraduates. Topic must be approved by the supervisor, and a formal final report must be presented on completion of research. Graded pass/fail. Instructor: Staff.

CS 101 abc. Special Topics in Computer Science. *Units in accordance with work accomplished; offered by announcement. Prerequisites: CS 21 and CS 38, or instructor's permission.* The topics covered vary from year to year, depending on the students and staff. Primarily for undergraduates.

CS 102 abc. Seminar in Computer Science. *3, 6, or 9 units as arranged with the instructor. Instructor's permission required.*

CS 103 abc. Reading in Computer Science. *3, 6, or 9 units as arranged with the instructor. Instructor's permission required.*

ACM/CS 114. Parallel Algorithms for Scientific Applications. *9 units.* For course description, see Applied and Computational Mathematics.

CS 116. Reasoning about Program Correctness. *9 units (3-0-6); first term. Prerequisite: CS 1 or equivalent.* This course presents the use of logic and formal reasoning to prove the correctness of sequential and concurrent programs. Topics in logic include propositional logic, basics of first-order logic, and the use of logic notations for specifying programs. The course presents a programming notation and its formal semantics, Hoare logic and its use in proving program correctness, predicate transformers and weakest preconditions, and fixed-point theory and its application to proofs of programs. Instructor: Joshi.

Ma/CS 117 abc. Computability Theory. *9 units (3-0-6).* For course description, see Mathematics.

CS 118. Logic Model Checking for Formal Software Verification. *9 units (3-3-3); second term.* An introduction to the theory and practice of logic model checking as an aid in the formal proofs of correctness of concurrent programs and system designs. The specific focus is on automata-theoretic verification. The course includes a study of the theory underlying formal verification, the correctness of programs, and the use of software tools in designs. Instructor: Holzmann.

CS 119. Reliable Software: Testing and Monitoring. *9 units (3-3-3); third term. Prerequisites: CS 1 or equivalent; CS 116 and CS 118 are recommended.* The class discusses theoretical and practical aspects of software testing and monitoring. Topics include finite state machine testing algorithms, random testing, constraint-based testing, coverage measures, automated debugging, logics and algorithms for runtime monitoring, and aspect-oriented approaches to monitoring. Emphasis is placed on automation. Students will be expected to develop and use software testing and monitoring tools to develop reliable software systems. Instructor: Staff.

EE/Ma/CS 127. Error-Correcting Codes. *9 units (3-0-6).* For course description, see Electrical Engineering.

CS/EE/Ma 129 abc. Information and Complexity. *9 units (3-0-6), first and second terms; (1-4-4) third term. Prerequisite: basic knowledge of probability and discrete mathematics.* A basic course in information theory and computational complexity with emphasis on fundamental concepts and tools that equip the student for research and provide a foundation for pattern recognition and learning theory. *First term:* what information is and what computation is; entropy, source coding, Turing machines, uncomputability. *Second term:* topics in information and complexity; Kolmogorov complexity, channel coding, circuit complexity, NP-completeness. *Third term:* theoretical and experimental projects on current research topics. Not offered 2010–11.

ME/CS 132 ab. Advanced Robotics: Navigation and Vision. *9 units (3-6-0).* For course description, see Mechanical Engineering.

CS 138 abc. Computer Algorithms. *9 units (3-0-6); first, second, third terms. Prerequisites: CS 21 and CS 38, or instructor's permission.* Design and analysis of algorithms. Techniques for problems concerning graphs, flows, number theory, string matching, data compression, geometry, linear algebra and coding theory. Optimization, including linear programming. Randomization. Basic complexity theory and cryptography. Not offered 2010–11.

CS 139 abc. Concurrency in Computation. *9 units (3-0-6); first, second, third terms. Prerequisites: CS 21 and CS 38, or instructor's permission.* Design and verification of concurrent algorithms. Topics: different models of concurrent computations; process synchronization by shared variables and synchronization primitives; distributed processes communicating by message exchange; the concepts of synchronization, indivisible actions, deadlock, and fairness; semantics and correctness proofs; implementation issues; and application to VLSI algorithm design. Parallel machine architecture issues include mapping a parallel algorithm on a network of processors, and classical parallel algorithms and their complexity. Not offered 2010–11.

CS 141 abc. Distributed Computation Laboratory. *9 units (3-3-3); first, second, third terms. Prerequisites: CS 3, CS 21 and CS 38, or instructor's permission.* This laboratory course deals with the systematic design and implementation of high-confidence scalable networks of communicating objects that discover other objects, configure themselves into collaborating groups of objects, and adapt to their environment. Teams of students explore theories and methods of implementation to obtain predictability and adaptability in distributed systems. Each team of students is expected to submit a research paper at the end of the third term, schedule demonstrations periodically, and maintain documents describing their project status. Instructor: Chandy. Given in alternate years; only (a) offered 2010–11.

CS/EE 143. Communication Networks. *9 units (3-3-3); first term. Prerequisite: Ma 2 ab.* This course introduces the basic mechanisms and protocols in communication networks, and mathematical models for their analysis. It covers topics such as digitization, switching, switch design, routing, error control (ARQ), congestion control, layering, queuing models, optimization models, basics of protocols in the Internet, wireless networks, and optical networks. This course can be combined with CS/EE 144 and CS/EE 145 to satisfy the project requirement for CS undergraduate degree. Instructor: Low.

CS/EE 144. Ideas behind the Web. *9 units (3-0-6); second term. Prerequisite: Ma 2 ab.* The Web is an essential part of our lives, and we all depend on it every day, but do you really know what makes it work? This course studies the "big" ideas behind the Web: How do search engines work? How can search engines make so much money from putting ads next to their search results? Are there ways to prevent spammers from accumulating lots of e-mail addresses? What does the Web actually look like? How big is the Web? For all these questions and more, the course will provide a mixture of both mathematical models and real-world, hands-on labs. This course can be combined with CS/EE 143 and CS/EE 145 to satisfy project requirement for CS undergraduate degree. Instructor: Wierman.

CS/EE 145. Projects in Networking. *9 units (0-0-9); third term. Prerequisites: CS/EE 143, CS/EE 144.* Students are expected to execute a substantial project in networking, write up a report describing their work, and make a presentation. This course can be combined with CS/EE 143 and CS/EE 144 to satisfy the project requirement for CS undergraduate degree. Instructors: Low, Wierman.

CS/EE 146. Advanced Networking. *9 units (3-3-3); third term. Prerequisite: CS/EE 143 or instructor's permission.* This is a research-oriented course meant for undergraduates and beginning graduate students who want to learn about current research topics in networks such as the Internet, power networks, social networks, etc. The topics covered in the course will vary, but will be pulled from current research topics in the design, analysis, control, and optimization of networks, protocols, and Internet applications. Usually offered in alternate years. Instructor: Wierman.

CS/EE 147. Network Performance Analysis. *9 units (3-0-6); third term. Prerequisite: Ma 2 ab is required. CS/EE 143, CS/EE 144, and ACM 116 are recommended.* When designing a network protocol, distributed system, etc., it is essential to be able to quantify the performance impacts of design choices along the way. For example, should we invest in more buffer space or a faster processor? One fast disk or multiple slower disks? How should requests be scheduled? What dispatching policy will work best? Ideally, one would like to make these choices before investing the time and money to build a system. This class will teach students how to answer this type of "what if" question by introducing students to analytic performance modeling, the tools necessary for rigorous system design. The course will focus on the mathematical tools of performance analysis (which include stochastic modeling, scheduling theory, and queueing theory) but will also highlight applications of these tools to real systems. Usually offered in alternate years. Not offered 2010–11.

EE/CNS/CS 148 ab. Selected Topics in Computational Vision. *9 units (3-0-6).* For course description, see Electrical Engineering.

CS 150. Probability and Algorithms. *9 units (3-0-6); second term. Prerequisites: CS 38 a and Ma 5 abc.* Elementary randomized algorithms and algebraic bounds in communication, hashing, and identity testing. Game tree evaluation. Topics may include randomized parallel computation; independence, k-wise independence and derandomization; rapidly mixing Markov chains; expander graphs and their applications; clustering algorithms. Instructor: Schulman.

CS 151. Complexity Theory. *9 units (3-0-6); third term. Prerequisites: CS 21 and CS 38, or instructor's permission.* This course describes a diverse array of complexity classes that are used to classify problems according to the computational resources (such as time, space, randomness, or parallelism) required for their solution. The course examines problems whose fundamental nature is exposed by this framework, the known relationships between complexity classes, and the numerous open problems in the area. Instructor: Umans.

CS 153. Current Topics in Theoretical Computer Science. *9 units (3-0-6); third term. Prerequisites: CS 21 and CS 38, or instructor's permission.* May be repeated for credit, with permission of the instructor. Students in this course will study an area of current interest in theoretical computer science. The lectures will cover relevant background material at an advanced level and present results from selected recent papers within that year's chosen theme. Students will be expected to read and present a research paper. Offered in alternate years. Instructor: Schulman.

CS/CNS/EE 154. Artificial Intelligence. *9 units (3-3-3); first term. Prerequisites: Ma 2 b or equivalent, and CS 1 or equivalent.* How can we build systems that perform well in unk nown environments and unforeseen situations? How can we develop systems that exhibit "intelligent" behavior, without prescribing explicit rules? How can we build systems that learn from experience in order to improve their performance? We will study core modeling techniques and algorithms from statistics, optimization, planning, and control and study applications in areas such as sensor networks, robotics, and the Internet. The course is designed for upper-level undergraduate and graduate students. Instructor: Krause.

CS/CNS/EE 155. Probabilistic Graphical Models. *9 units (3-3-3); second term. Prerequisite: background in algorithms and statistics (CS/CNS/EE 154 or CS/CNS/EE 156 a or instructor's permission).* Many real-world problems in AI, computer vision, robotics, computer systems, computational neuroscience, computational biology, and natural language processing require one to reason about highly uncertain, structured data, and draw global insight from local observations. Probabilistic graphical models allow addressing these challenges in a unified framework. These models generalize approaches such as hidden Markov models and Kalman filters, factor analysis, and Markov random fields. In this course, we will study the problem of learning such models from data, performing inference (both exact and approximate), and using these models for making decisions. The techniques draw from statistics, algorithms, and discrete and convex optimization. The course will be heavily research-oriented, covering current developments such as probabilistic relational models, models for naturally combining logical and probabilistic inference, and nonparametric Bayesian methods. Instructor: Krause.

CS/CNS/EE 156 ab. Learning Systems. *9 units (3-0-6); first, second terms. Prerequisites: Ma 2 and CS 2, or equivalent.* Introduction to the theory, algorithms, and applications of automated learning. How much information is needed to learn a task, how much computation is involved, and how it can be accomplished. Special emphasis will be given to unifying the different approaches to the subject coming from statistics, function approximation, optimization, pattern recognition, and neural networks. Not offered 2010–11.

CS/CNS/EE 159. Projects in Machine Learning and AI. *9 units (0-0-9); third term. Prerequisite: CS/CNS/EE 154 or CS/CNS/EE 156 b.* Students are expected to execute a substantial project in AI and/or machine learning, write up a report describing their work, and make a presentation. This course can be combined with CS/CNS/EE 154/155 or with CS/CNS/EE 156 ab to satisfy the project requirement for the CS undergraduate degree. Not offered 2010–11.

CS/CNS 171. Introduction to Computer Graphics Laboratory. *12 units (3-6-3); first term. Prerequisites: Ma 2 and extensive programming experience.* This course introduces the basic ideas behind computer graphics and its fundamental algorithms. Topics include graphics input and output, the graphics pipeline, sampling and image manipulation, three-dimensional transformations and interactive modeling, basics of physically based modeling and animation, simple shading models and their hardware implementation, and fundamental algorithms of scientific visualization. Students will be required to perform significant implementations. Instructor: Barr.

CS/CNS 174. Computer Graphics Projects. *12 units (3-6-3); third term. Prerequisites: Ma 2 and CS/CNS 171 or instructor's permission.* This laboratory class offers students an opportunity for independent work covering recent computer graphics research. In coordination with the instructor, students select a computer graphics modeling, rendering, interaction, or related algorithm and implement it. Students are required to present their work in class and discuss the results of their implementation and any possible improvements to the basic methods. May be repeated for credit with instructor's permission. Instructor: Barr.

CS 176. Introduction to Computer Graphics Research. *9 units (3-3-3); second term. Prerequisite: CS/CNS 171, or 173, or 174.* The course will go over recent research results in computer graphics, covering subjects from mesh processing (acquisition, compression, smoothing, parameterization, adaptive meshing), simulation for purposes of animation, rendering (both photo- and nonphotorealistic), geometric modeling primitives (image based, point based), and motion capture and editing. Other subjects may be treated as they appear in the recent literature. The goal of the course is to bring students up to the frontiers of computer graphics research and prepare them for their own research. Instructor: Desbrun.

CS 177. Discrete Differential Geometry: Theory and Applications. *9 units (3-3-3); first term.* Topics include, but are not limited to, discrete exterior calculus; Whitney forms; DeRham and Whitney complexes; Morse theory; computational and algebraic topology; discrete simulation of thin shells, fluids, electromagnetism, elasticity; surface parameterization; Hodge decomposition. Instructor: Desbrun.

CS 180. Master's Thesis Research. *Units (total of 45) are determined in accordance with work accomplished.*

CS/EE 181 abc. VLSI Design Laboratory. *12 units (3-6-3); first, second, third terms.* Digital integrated system design, with projects involving the design, verification, and testing of high-complexity CMOS microcircuits. First-term lecture and homework topics emphasize disciplined design, and include CMOS logic, layout, and timing; computer-aided design and analysis tools; and electrical and performance considerations. Each student is required in the first term to complete individually the design, layout, and verification of a moderately complex integrated circuit. Advanced topics second and third terms include self-timed design, computer architecture, and other topics that vary year by year. Projects are large-scale designs done by teams. Instructor: Martin. Only (a) and (b) offered 2010–11.

CS/EE 184 ab. Computer Architecture. *9 units (3-3-3); second, third terms. Prerequisites: CS 21 and CS 24, or instructor's permission.* Organization and design of physical computational systems, basic building blocks for computations, understanding and exploiting structure in computational problems, design space, costs, and trade-offs in computer organization, common machine abstractions, and implementation/optimization techniques. The course will develop the fundamental issues and trade-offs that define computer organizational and architectural styles, including RISC, VLIW, Super Scalar, EPIC, SIMD, Vector, MIMD, reconfigurable, FPGA, PIM, and SoC. Basic topics in the design of computational units, instruction organization, memory systems, control and data flow, interconnect, and the hardware-software abstraction will also be covered. Not offered 2010–11.

CS 185 abc. Asynchronous VLSI Design Laboratory. *9 units (3-3-3); first, second, third terms. Prerequisite: CS 139.* The design of digital integrated circuits whose correct operation is independent of delays in wires and gates. (Such circuits do not use clocks.) Emphasis is placed on high-level synthesis, design by program transformations, and correctness by construction. The first term introduces delay-insensitive design techniques, description of circuits as concurrent programs, circuit compilation, standard-cell layout and other computer-aided design tools, and electrical optimizations. The second term is reserved for advanced topics, and for the presentation and review of mid-size projects, which will be fabricated in CMOS or GaAs technologies, and tested. Not offered 2010–11.

CNS/Bi/Ph/CS 187. Neural Computation. *9 units (3-0-6).* For course description, see Computation and Neural Systems.

CNS/CS/EE 188. Topics in Computation and Biological Systems. *9 units (3-0-6).* For course description, see Computation and Neural Systems.

BE/CS/CNS/Bi 191 ab. Biomolecular Computation. *9 units.* For course description, see Bioengineering.

Ph/CS 219 abc. Quantum Computation. *9 units (3-0-6); first, second, third terms.* For course description, see Physics.

SS/CS 241 ab. Introduction to Social and Information Sciences. *9 units (3-0-6).* For course description, see Social Science.

CS/EE 245. Special Topics in Networking. *9 units (3-3-3); second term. Prerequisites: CS/EE 143 and CS/EE 144 or instructor's permission.* This course is an advanced, research-oriented seminar in communication networks meant for graduate students and advanced undergraduates. The topics covered in the course will vary, but will always come from the cutting edge of networking research. Examples of possible topics are error-correcting codes, wireless networking, scheduling theory, and congestion control. Instructor: Low.

CS/CNS/EE 253. Special Topics in Machine Learning. *9 units (3-3-3). Prerequisite: CS/CNS/EE 154 or CS/CNS/EE 156 a or instructor's permission.* This course is an advanced, research-oriented seminar in machine learning and AI meant for graduate students and advanced undergraduates. The topics covered in the course will vary, but will always come from the cutting edge of machine learning and AI research. Examples of possible topics are active learning and optimized information gathering, AI in distributed systems, computational learning theory, machine learning applications (on the Web, in sensor networks and robotics). Not offered 2010–11.

CS 274 abc. Topics in Computer Graphics. *9 units (3-3-3); first, second, third terms. Prerequisite: instructor's permission.* Each term will focus on some topic in computer graphics, such as geometric modeling, rendering, animation, human-computer interaction, or mathematical foundations. The topics will vary from year to year. May be repeated for credit with instructor's permission. Not offered 2010–11.

CS 280. Research in Computer Science. *Units in accordance with work accomplished. Approval of student's research adviser and option adviser must be obtained before registering.*

CS 282 abc. Reading in Computer Science. *6 units or more by arrangement; first, second, third terms. Instructor's permission required.*

CS 286 abc. Seminar in Computer Science. *3, 6, or 9 units, at the instructor's discretion. Instructor's permission required.*

CONTROL AND DYNAMICAL SYSTEMS

CDS 90 abc. Senior Thesis in Control and Dynamical Systems. *9 units (0-0-9); first, second, third terms. Prerequisite: CDS 110 ab or CDS 140 ab (may be taken concurrently).* Research in control and dynamical systems, supervised by a Caltech faculty member. The topic selection is determined by the adviser and the student and is subject to approval by the CDS faculty. First and second terms: midterm progress report and oral presentation during finals week. Third term: completion of thesis and final presentation. Not offered on a pass/fail basis. Instructor: Murray.

CDS 101. Design and Analysis of Feedback Systems. *6 units (2-0-4); first term. Prerequisites: Ma 1 and Ma 2 or equivalents.* An introduction to feedback and control in physical, biological, engineering, and information sciences. Basic principles of feedback and its use as a tool for altering the dynamics of systems and managing uncertainty. Key themes throughout the course will include input/output response, modeling and model reduction, linear vs. nonlinear models, and local vs. global behavior. This course is taught concurrently with CDS 110 a, but is intended for students who are interested primarily in the concepts and tools of control theory and not the analytical techniques for design and synthesis of control systems. Instructor: MacMynowski.

CDS 104. Introductory Concepts for Dynamical Systems. *9 units (3-0-6); third term. Prerequisites: Ma 1, Ma 2 (or equivalent).* This course teaches basic concepts in mathematics and dynamics that are required for CDS 110 and CDS 140. It is intended as a tutorial for nonmajors who plan to do further course work in CDS but may not have adequate preparation in linear algebra and ordinary differential equations. Topics to be covered include linear ODEs in one variable, linear algebra, eigenvalues and eigenvectors, coupled linear ODEs, stability of ODEs. Extensive use of examples based on modeling of physical, biological, and information systems using differential equations and linear algebra. Instructor: Staff.

CDS 110 ab. Introductory Control Theory. *12 units (3-0-9) first, 9 units (3-0-6) second terms. Prerequisites: Ma 1 and Ma 2 or equivalents; ACM 95/100 may be taken concurrently.* An introduction to analysis and design of feedback control systems, including classical control theory in the time and frequency domain. Modeling of physical, biological, and information systems using linear and nonlinear differential equations. Stability and performance of interconnected systems, including use of block diagrams, Bode plots, the Nyquist criterion, and Lyapunov functions. Robustness and uncertainty management in feedback systems through stochastic and deterministic methods. Introductory random processes, Kalman filtering, and norms of signals and systems. The first term of this course is taught concurrently with CDS 101, but includes additional lectures, reading, and homework that is focused on analytical techniques for design and synthesis of control systems. Instructor: MacMynowski.

CDS 140 ab. Introduction to Dynamics. *9 units (3-0-6); second, third terms. Prerequisite: ACM 95 or equivalent.* Basics in topics in dynamics in Euclidean space, including equilibria, stability, Lyapunov functions, periodic solutions, Poincaré-Bendixon theory, Poincaré maps. Attractors and structural stability. The Euler-Lagrange equations, mechanical systems, small oscillations, dissipation, energy as a Lyapunov function, conservation laws. Introduction to simple bifurcations and eigenvalue crossing conditions. Discussion of bifurcations in applications, invariant manifolds, the method of averaging, Melnikov's method, and the Smale horseshoe. Instructors: Marsden, Murray, staff.

CDS 190. Independent Work in Control and Dynamical Systems. *Units to be arranged; first, second, third terms; maximum two terms. Prerequisite: CDS 110 ab or CDS 140 ab.* Research project in control and dynamical systems, supervised by a CDS faculty member.

CDS 201. Linear Algebra and Applied Operator Theory. *9 units (3-0-6); first term.* Linear spaces, subspaces, spans of sets, linear independence, bases, dimensions; linear transformations and operators, examples, nullspace/kernel, range-space/image, one-to-one and onto, isomorphism and invertibility, rank-nullity theorem; products of linear transformations, left and right inverses, generalized inverses. Adjoints of linear transformations, singular-value decomposition and Moore-Penrose inverse; matrix representation of linear transformations between finite-dimensional linear spaces, determinants, multilinear forms; metric spaces: examples, limits and convergence of sequences, completeness, continuity, fixed-point (contraction) theorem, open and closed sets, closure; normed and Banach spaces, inner product and Hilbert spaces: examples, Cauchy-Schwarz inequality, orthogonal sets, Gram-Schmidt orthogonalization, projections onto subspaces, best approximations in subspaces by projection; bounded linear transformations, principle of superposition for infinite series, well-posed linear problems, norms of operators and matrices, convergence of sequences and series of operators; eigenvalues and eigenvectors of linear operators, including their properties for self-adjoint operators, spectral theorem for self-adjoint and normal operators; canonical representations of linear operators (finite-dimensional case), including diagonal and Jordan form, direct sums of (generalized) eigenspaces. Schur form; functions of linear operators, including exponential, using diagonal and Jordan forms, Cayley-Hamilton theorem. Taught concurrently with ACM 104. Instructor: Beck.

CDS 202. Geometry of Nonlinear Systems. *9 units (3-0-6); second term. Prerequisite: CDS 201 or AM 125 a.* Basic differential geometry, oriented toward applications in control and dynamical systems. Topics include smooth manifolds and mappings, tangent and normal bundles. Vector fields and flows. Distributions and Frobenius's theorem. Matrix Lie groups and Lie algebras. Exterior differential forms, Stokes' theorem. Instructor: Staff.

CDS 205. Geometric Mechanics. *9 units (3-0-6); third term. Prerequisites: CDS 202, CDS 140.* The geometry and dynamics of Lagrangian and Hamiltonian systems, including symplectic and Poisson manifolds, variational principles, Lie groups, momentum maps, rigid-body dynamics, Euler-Poincaré equations, stability, and an introduction to reduction theory. More advanced topics (taught in a course the following year) will include reduction theory, fluid dynamics, the energy momentum method, geometric phases, bifurcation theory for mechanical systems, and nonholonomic systems. Instructor: Marsden. Given in alternate years; not offered 2010–11.

CDS 212. Introduction to Modern Control. *9 units (3-0-6); first term. Prerequisites: ACM 95/100 abc or equivalent; CDS 110 ab or equivalent.* Introduction to modern control systems with emphasis on the role of control in overall system analysis and design. Examples drawn from throughout engineering and science. Open versus closed loop control. State-space methods, time and frequency domain, stability and stabilization, realization theory. Time-varying and nonlinear models. Uncertainty and robustness. Instructor: Doyle.

CDS 213. Robust Control. *9 units (3-0-6); second term. Prerequisites: CDS 212, CDS 201.* Linear systems, realization theory, time and frequency response, norms and performance, stochastic noise models, robust stability and performance, linear fractional transformations, structured uncertainty, optimal control, model reduction, m analysis and synthesis, real parametric uncertainty, Kharitonov's theorem, uncertainty modeling. Instructor: Doyle.

CDS 270. Advanced Topics in Systems and Control. *Hours and units by arrangement.* Topics dependent on class interests and instructor. May be repeated for credit.

CDS 280. Advanced Topics in Geometric Mechanics or Dynamical Systems Theory. *Hours and units by arrangement. Prerequisite: instructor's permission.* Topics will vary according to student and instructor interest. Examples include chaotic transport theory, invariant manifold techniques, multidimensional geometric perturbation theory, the dynamics of coupled oscillators, rigid-body dynamics, numerical methods in dynamical systems theory. May be repeated for credit. Instructor: Marsden.

CDS 300 abc. Research in Control and Dynamical Systems. *Hours and units by arrangement.* Research in the field of control and dynamical systems. By arrangement with members of the staff, properly qualified graduate students are directed in research. Instructor: Staff.

ECONOMICS

Ec 11. Introduction to Economics. *9 units (3-2-4); first, third terms.* An introduction to economic methodology, models, and institutions. Includes both basic microeconomics and an introduction to modern approaches to macroeconomic issues. Students are required to participate in economics experiments. Instructors: Plott, Rangel.

BEM/Ec/SS 20. Scientific Writing and Oral Presentation in the Social Sciences. *6 units (2-0-4).* For course description, see Business Economics and Management.

Ec 98 abc. Senior Research and Thesis. *Prerequisite: instructor's permission.* Senior economics majors wishing to undertake research may elect a variable number of units, not to exceed 12 in any one term, for such work under the direction of a member of the economics faculty.

Ec 101. Selected Topics in Economics. *9 units (3-0-6); offered by announcement.* Instructors: Staff, visiting lecturers.

Ec 105. Industrial Organization. *9 units (3-0-6); second term. Prerequisite: Ec 11 or equivalent.* A study of how technology affects issues of market structure and how market structure affects observable economic outcomes, such as prices, profits, advertising, and research and development expenditures. Emphasis will be on how the analytic tools developed in the course can be used to examine particular industries in detail. Instructor: Amir.

Ec 106. Topics in Applied Industrial Organization. *9 units (3-0-6); first term. Prerequisite: Ec 11; Ec 116 recommended.* Topics include simulation of mergers in oligopolistic industries, valuation of intellectual property, price setting and concentration in the pharmaceutical market, and statistical analysis of combined tobacco and asbestos exposure. A term paper will be required. Instructor: Shum.

Ec 116. Contemporary Socioeconomic Problems. *9 units (3-0-6). Prerequisites: Ec 11 and PS 12 or equivalents.* An analytical investigation of the economic aspects of certain current social issues. Topics: the economics of education, medical-care systems, urban affairs, and the welfare system. Not offered 2010–11.

BEM/Ec 118. Environmental Economics. *9 units (3-0-6).* For course description, see Business Economics and Management.

Ec 121 ab. Theory of Value. *9 units (3-0-6); first, second terms. Prerequisites: Ec 11 and Ma 2 (may be taken concurrently).* A study of consumer preference, the structure and conduct of markets, factor pricing, measures of economic efficiency, and the interdependence of markets in reaching a general equilibrium. Instructors: Ortoleva, Border.

Ec 122. Econometrics. *9 units (3-0-6); first term. Prerequisite: Ma 112 a.* The application of statistical techniques to the analysis of economic data. Instructor: Sherman.

Ec 123. Macroeconomics. *9 units (3-0-6); third term. Prerequisite: Ec 11 and modest ability to program in Matlab or Mathematica.* The role of time and uncertainty in understanding the behavior of economic aggregates such as investment, employment, and price levels. Emphasis is on representative-agent recursive equilibrium models. Topics include practical dynamic programming; job search, matching, and unemployment; asset pricing; monetary and fiscal policy; and taxation and insurance. Not offered 2010–11.

Ec/SS 124. Introduction to Empirical Process Methods. *9 units (3-0-6); second term. Prerequisite: Ec 122.* Standard estimators (e.g., maximum likelihood estimators) of parameters in econometric models optimize smooth criterion functions. Inference is typically based on asymptotic approximations which exploit smoothness. New estimators have been developed that optimize non-smooth criterion functions, and for which standard analysis does not apply. This course develops tools needed to do asymptotic inference with such estimators—moment maximal inequalities for empirical processes (standardized averages). We show how to apply these methods to analyze various recent estimators. Instructor: Sherman.

Ec/SS 129. Economic History of the United States. *9 units (3-0-6); second term. Prerequisite: Ec 11 or SS 13.* An examination of certain analytical and quantitative tools and their application to American economic development. Not offered 2010–11.

Ec/SS 130. Economic History of Europe from the Middle Ages to the Industrial Revolution. *9 units (3-0-6); first term. Prerequisite: Ec 11 or SS 13.* Employs the theoretical and quantitative techniques of economics to help explore and explain the development of the European cultural area between 1000 and 1850. Topics include the rise of commerce, the demographic transition, the industrial revolution, and changes in property rights and capital markets. Instructor: Bogart.

Ec 131. Market Design. *9 units (3-0-6); first term. Prerequisite: Ec 11 or equivalent.* This course studies the design of markets, focusing on efficient organizations and the incentives created by market rules. Applications include online auction markets, government auctions of natural resources, matching markets (e.g., students to classes or schools or kidneys to recipients), and electricity and gas markets. It will examine the details of real-world markets, using game theoretic analysis, empirical analysis, and experimental work. Instructor: Bossaerts.

Ec 132. Auctions. *9 units (3-0-6). Prerequisite: Ec 11.* The course covers basic topics in auction theory (private and common value auctions, revenue equivalence, reserve prices, budget constraints, risk aversion, etc.) and discusses more advanced theory such as mechanism design, multi-unit auctions, and interdependent valuations. Experimental studies of auctions will be reviewed where appropriate. The course will also discuss practical considerations that arise when designing auctions to sell licenses in a particular industry. Not offered 2010–11.

Ec 140. Economic Progress. *9 units (3-0-6); second term. Prerequisites: Ec 11 and Ma 2; Ec 122 recommended.* This course examines the contemporary literature on economic growth and development from both a theoretical and historical/empirical perspective. Topics include a historical overview of economic progress and the lack thereof; simple capital accumulation models; equilibrium/planning models of accumulation; endogenous growth models; empirical tests of convergence; the measurement and role of technological advancement; and the role of trade, institutions, property rights, human capital, and culture. Instructor: Border.

Ec 145. Public Finance. *9 units (3-0-6). Prerequisite: Ec 11 or equivalent.* An intermediate-level course on the economics of the public sector. Material is chosen from welfare economics, public expenditure theory and practice, taxation theory and practice, federalism, and public choice theory. Not offered 2010–11.

BEM/Ec 146. Organization Design. *9 units (3-0-6).* For course description, see Business Economics and Management.

Ec/PS 160 abc. Laboratory Experiments in the Social Sciences. *9 units (3-3-3); first, second, third terms. Section a required for sections b and c.* An examination of recent work in laboratory testing in the social sciences with particular reference to work done in social psychology, economics, and political science. Students are required to design and conduct experiments. Instructor: Plott.

PS/Ec 172. Game Theory. *9 units (3-0-6).* For course description, see Political Science.

PS/Ec 173. Cooperation and Social Behavior. *9 units (3-0-6).* For course description, see Political Science.

Ec 181. Convex Analysis and Economic Theory. *9 units (3-0-6); first term. Prerequisites: Ma 2 ab, Ec 121 a.* Introduction to the use of convex analysis in economic theory. Includes a rigorous discussion of separating hyperplane theorems, continuity and differentiability properties of convex and concave functions, support functions, subdifferentials, Fenchel conjugacy, saddle-point theory, theorem of the alternative, and linear programming. Emphasis is on the finite-dimensional case, but infinite-dimensional spaces will be discussed. Applications to the theory of cost and production functions, decision theory, and game theory. Instructor: Border.

BEM/Ec 185. Political Economy of Corporate Governance. *9 units (3-0-6).* For course description, see Business Economics and Management.

BEM/Ec 187. Corporate Finance and Financial Intermediaries. *9 units (3-0-6).* For course description, see Business Economics and Management.

Ec/PS 190. Undergraduate Research. *Units to be arranged; any term. Prerequisite: advanced economics course and instructor's permission.* This course offers advanced undergraduates the opportunity to pursue research in political science or economics. Graded pass/fail.

ELECTRICAL ENGINEERING

EE 1. Introduction to Electrical Engineering Seminar. *1 unit; second term.* Required for EE undergraduates. Weekly seminar given by faculty in the department broadly describing different areas of electrical engineering: circuits and VLSI, communications, control, devices, images and vision, information theory, learning and pattern recognition, MEMS and micromachining, networks, electromagnetics and opto-electronics, RF and microwave circuits and antennas, robotics and signal processing, and specifically, research going on at Caltech. Instructor: Staff.

EE 5. Introduction to Embedded Systems. *6 units (2-3-1); third term.* This course is intended to give the student a basic understanding of the major hardware and software principles involved in the specification and design of embedded systems. Topics include basic digital logic, CPU and embedded system architecture, and embedded systems programming principles (events, user interfaces, and multitasking). The class is intended for students who wish to gain a basic understanding of embedded systems or for those who would like an introduction to the material before taking EE/CS 51/52. Graded pass/fail. Instructor: George.

APh/EE 9 ab. Solid-State Electronics for Integrated Circuits. *6 units (2-2-2).* For course description, see Applied Physics.

EE 40. Introduction to Semiconductors and Sensors. *9 units (3-0-6); third term. Prerequisites: APh/EE 9 ab, Ma 2, Ph 2.* This course provides an introduction to semiconductors and semiconductor sensors. The fundamental physics of semiconductor electronics and devices will be emphasized, together with their applications. Devices that will be discussed include photoconductors, diodes, transistors, CCDs, MOS/MOSFET/MOS imagers, temperature sensors, magnetic sensors, thermoelectricity, piezoresistivity, piezoelectrics, etc. Instructor: Tai.

EE 45. Electronics Laboratory. *12 units (3-3-6); third term. Prerequisites: should be taken concurrently with EE 40, or with instructor's permission; Ma 2 a, Ph 1abc.* Fundamentals of electronics and circuit analysis. Lectures and laboratory sessions on linear circuits, transient response, steady-state sinusoidal response and phasors, transformers, diodes, transistors, small-signal analysis, gain stages, operational amplifiers; an introduction to electrical and analog electronic systems such as radio and audio systems. Instructor: Emami.

EE/CS 51. Principles of Microprocessor Systems. *12 units (4-5-3); first term.* The principles and design of microprocessor-based computer systems. Lectures cover both hardware and software aspects of microprocessor system design such as interfacing to input and output devices, user interface design, real-time systems, and table-driven software. The homework emphasis is on software development, especially interfacing with hardware, in assembly language. Instructor: George.

EE/CS 52. Microprocessor Systems Laboratory. *12 units (1-11-0); second term. Prerequisite: EE/CS 51 or equivalent.* The student will design, build, and program a specified microprocessor-based system. This structured laboratory is organized to familiarize the student with electronic circuit construction techniques, modern development facilities, and standard design techniques. The lectures cover topics in microprocessor system design such as display technologies, interfacing with analog systems, and programming microprocessors in high-level languages. Instructor: George.

EE/CS 53 abc. Microprocessor Project Laboratory. *12 units (0-12-0); first, second, third terms. Prerequisite: EE/CS 52 or equivalent.* A project laboratory to permit the student to select, design, and build a microprocessor-based system. The student is expected to take a project from proposal through design and implementation (possibly including PCB fabrication) to final review and documentation. Instructor: George.

CS/EE/ME 75 abc. Introduction to Multidisciplinary Systems Engineering. *3 units (2-0-1) first term; 3–6 units second term; 12 units (2-9-1) or up to 18 units (2-15-1) third term.* For course description, see Computer Science.

EE 80 abc. Senior Thesis. *9 units; first, second, third terms. Prerequisite: instructor's permission, which should be obtained during the junior year to allow sufficient time for planning the research.* Individual research project, carried out under the supervision of a member of the electrical engineering or computer science faculty. Project must include significant design effort. Written report required. Open only to senior electrical engineering, computer science, or electrical and computer engineering majors. Not offered on a pass/fail basis. Instructor: Potter.

EE 90. Analog Electronics Project Laboratory. *9 units (1-8-0); second, third terms. Prerequisites: EE 40 and EE 45.* A structured laboratory course that gives the student the opportunity to design and build a sequence of simple analog electronics projects. The goal is to gain familiarity with circuit design and construction, component selection, CAD support, and debugging techniques. Instructor: Megdal.

EE 91 ab. Experimental Projects in Electronic Circuits. *Units by arrangement; first, second terms. 12 units minimum each term. Prerequisite: EE 45. Recommended: EE/CS 51 and 52, and EE 114 ab (may be taken concurrently). Open to seniors; others only with instructor's permission.* An opportunity to do advanced original projects in analog or digital electronics and electronic circuits. Selection of significant projects, the engineering approach, modern electronic techniques, demonstration and review of a finished product. DSP/microprocessor development support and analog/digital CAD facilities available. Text: literature references. Instructor: Megdal.

EE 99. Advanced Work in Electrical Engineering. *Units to be arranged.* Special problems relating to electrical engineering will be arranged. For undergraduates; students should consult with their advisers. Graded pass/fail.

EE 105 abc. Electrical Engineering Seminar. *1 unit; first, second, third terms.* All candidates for the M.S. degree in electrical engineering are required to attend any graduate seminar in any division each week of each term. Graded pass/fail. Instructor: Hassibi.

EST/EE/ME 109 ab. Energy. *9 units(3-0-6.)* For course description, see Energy Science and Technology.

EE 111. Signals, Systems, and Transforms. *9 units (3-0-6); first term. Prerequisites: Ma 1, Ma 2. EE 45 recommended.* An introduction to continuous and discrete time signals and systems. Study of the Fourier transform, Fourier series, the Laplace transform, Z-transforms, and the fast Fourier transform as applied in electrical engineering. Various types of systems, with emphasis on linear and time invariant systems. Transfer functions, difference and differential equations, state space representations, system realizations with block diagrams, and analysis of transient and steady state responses. Sampling theorems for analog to digital conversion. Instructor: Vaidyanathan.

EE 112. Introduction to Digital Signal Processing. *9 units (3-0-6); second term. Prerequisite: EE 111 or equivalent.* Fundamentals of digital signal processing, digital representations, analog to digital conversions, fast Fourier transformation, digital filtering, filter structures, quantization and stability analysis, roundoff noise calculations, and applications in various areas. Instructor: Vaidyanathan. Given in alternate years; offered 2010–11.

EE 113. Feedback and Control Circuits. *12 units (4-4-4); third term. Prerequisite: EE 45 or equivalent.* This class studies the design and implementation of feedback and control circuits. The course begins with an introduction to basic feedback circuits, using both op amps and transistors. These circuits are used to study feedback principles, including circuit topologies, stability, and compensation. Following this, basic control techniques and circuits are studied, including PID (Proportional-Integrated-Derivative) control, digital control, and fuzzy control. There is a significant laboratory component to this course, in which the student will be expected to build, analyze, test, and measure the circuits and systems discussed in the lectures. Instructor: George.

EE 114 ab. Analog Circuit Design. *12 units (4-0-8); first, second terms. Prerequisites: EE 45 or equivalent, EE 114 a or equivalent.* Analysis and design of analog circuits at the transistor level. Emphasis on intuitive design methods, quantitative performance measures, and practical circuit limitations. Circuit performance evaluated by hand calculations and computer simulations. Recommended for seniors and graduate students. First term deals with continuous time and amplitude signals; physics of bipolar and MOS transistors, low-frequency behavior of single-stage and multistage amplifiers, current sources, active loads, differential amplifiers, operational amplifiers, and supply and temperature independent biasing. Second term covers high-frequency response of amplifiers, feedback in electronic circuits, stability of feedback amplifiers, and noise in electronic circuits. A number of the following topics will be covered each year: translinear circuits, switched capacitor circuits, data conversion circuits (A/D and D/A), continuous-time $G_m.C$ filters and phase locked loops. Instructor: Hajimiri.

ACM/EE 116. Introduction to Stochastic Processes and Modeling. *9 units (3-0-6).* For course description, see Applied and Computational Mathematics.

Ph/EE 118. Low-Noise Electronic Measurement. *9 units (3-0-6).* For course description, see Physics.

EE 119 abc. Advanced Digital Systems Design. *9 units (3-3-3); first, second, third terms. Prerequisite: EE/CS 52 or CS/EE 181 a.* Advanced digital design as it applies to the design of systems using PLDS and ASICs (in particular, gate arrays and standard cells). The course covers both design and implementation details of various systems and logic device technologies. The emphasis is on the practical aspects of ASIC design, such as timing, testing, and fault grading. Topics include synchronous design, state machine design, ALU and CPU design, application-specific parallel computer design, design for testability, PALs, FPGAs, VHDL, standard cells, timing analysis, fault vectors, and fault grading. Students are expected to design and implement both systems discussed in the class as well as self-proposed systems using a variety of technologies and tools. Not offered 2010–11.

EE 124. Mixed-mode Integrated Circuits. *9 units (3-0-6); third term. Prerequisite: EE 114 a or equivalent.* Introduction to selected topics in mixed-signal circuits and systems in highly scaled CMOS technologies. Design challenges and limitations in current and future technologies will be discussed through topics such as clocking (PLLs and DLLs), clock distribution networks, sampling circuits, high-speed transceivers, timing recovery techniques, equalization, monitor circuits, power delivery, and converters (A/D and D/A). A design project is an integral part of the course. Instructor: Emami.

EE 125. Digital Electronics and Design with FPGAs and VHDL. *9 units (3-6-0); second term. Prerequisite: basic knowledge of digital electronics.* Study of programmable logic devices (CPLDs and FPGAs). Detailed study of the VHDL language, with basic and advanced applications. Review and discussion of digital design principles for combinational-logic, combinational-arithmetic, sequential, and state-machine circuits. Detailed tutorials for synthesis and simulation tools using FPGAs and VHDL. Wide selection of complete, real-world fundamental advanced projects, including theory, design, simulation, and physical implementation. All designs are implemented using state-of-the-art development boards. Instructor: Pedroni.

EE/Ma 126 ab. Information Theory. *9 units (3-0-6); first, second terms. Prerequisite: Ma 2.* Shannon's mathematical theory of communication, 1948–present. Entropy, relative entropy, and mutual information for discrete and continuous random variables. Shannon's source and channel coding theorems. Mathematical models for information sources and communication channels, including memoryless, first-order Markov, ergodic, and Gaussian. Calculation of capacity-cost and rate-distortion functions. Kolmogorov complexity and universal source codes. Side information in source coding and communications. Network information theory, including multiuser data compression, multiple access channels, broadcast channels, and multiterminal networks. Discussion of philosophical and practical implications of the theory.

This course, when combined with EE 112, EE/Ma/CS 127, EE 161, and/or EE 167 should prepare the student for research in information theory, coding theory, wireless communications, and/or data compression. Instructor: Effros.

EE/Ma/CS 127. Error-Correcting Codes. *9 units (3-0-6); third term. Prerequisite: Ma 2.* This course, a sequel to EE/Ma 126 a, may be taken independently; it will develop from first principles the theory and practical implementation of the most important techniques for combating errors in digital transmission or storage systems. Topics include algebraic block codes, e.g., Hamming, Golay, Fire, BCH, Reed-Solomon (including a self-contained introduction to the theory of finite fields); and the modern theory of sparse graph codes with iterative decoding, e.g. LDPC codes, fountain coding. Emphasis will be placed on the associated encoding and decoding algorithms, and students will be asked to demonstrate their understanding with a software project. Instructor: Ho.

EE 128 ab. Selected Topics in Digital Signal Processing. *9 units (3-0-6); second, third terms. Prerequisites: EE 111 and EE 160 or equivalent required, and EE 112 or equivalent recommended.* The course focuses on several important topics that are basic to modern signal processing. Topics include multirate signal processing material such as decimation, interpolation, filter banks, polyphase filtering, advanced filtering structures and nonuniform sampling, optimal statistical signal processing material such as linear prediction and antenna array processing, and signal processing for communication including optimal transceivers. Not offered 2010–11.

CS/EE/Ma 129 abc. Information and Complexity. *9 units (3-0-6) first, second terms; (1-4-4) third term.* For course description, see Computer Science.

APh/EE 130. Electromagnetic Theory. *9 units (3-0-6).* For course description, see Applied Physics.

EE/APh 131. Optical Wave Propagation. *9 units (3-0-6); second term.* This course focuses on optical wave propagation and related applications. Topics to be covered include Huygens' principle, Fourier optics, Gaussian waves, imaging, gratings, spectroscopy, interferometry, Fabry-Perot cavities, coherence, holography, femtosecond optics, dispersion, Kramers-Kronig relation, Mie scattering theory, photonic band gaps, and near-field imaging. Instructor: Staff.

APh/EE 132. Optoelectronic Materials and Devices. *9 units (3-0-6).* For course description, see Applied Physics.

CS/EE 143. Communication Networks. *9 units (3-3-3).* For course description, see Computer Science.

CS/EE 144. Ideas behind the Web. *9 units (3-0-6).* For course description, see Computer Science.

CS/EE 145. Projects in Networking. *9 units (0-0-9).* For course description, see Computer Science.

CS/EE 146. Advanced Networking. *9 units (3-3-3).* For course description, see Computer Science.

CS/EE 147. Network Performance Analysis. *9 units (3-0-6).* For course description, see Computer Science.

EE/CNS/CS 148 ab. Selected Topics in Computational Vision. *9 units (3-0-6); first, third terms. Prerequisites: undergraduate calculus, linear algebra, geometry, statistics, computer programming.* The class will focus on an advanced topic in computational vision: recognition, vision-based navigation, 3-D reconstruction. The class will include a tutorial introduction to the topic, an exploration of relevant recent literature, and a project involving the design, implementation, and testing of a vision system. Instructor: Perona.

EE 150. Topics in Electrical Engineering. *Units to be arranged; terms to be arranged.* Content will vary from year to year, at a level suitable for advanced undergraduate or beginning graduate students. Topics will be chosen according to the interests of students and staff. Visiting faculty may present all or portions of this course from time to time. Instructor: Staff.

EE 151. Electromagnetic Engineering. *9 units (3-0-6); second term. Prerequisite: EE 45.* Foundations of circuit theory—electric fields, magnetic fields, transmission lines, and Maxwell's equations, with engineering applications. Instructor: Rutledge.

EE 153. Microwave Circuits and Antennas. *12 units (3-2-7); third term. Prerequisite: EE 45.* High-speed circuits for wireless communications, radar, and broadcasting. Design, fabrication, and measurements of microstrip filters, directional couplers, low-noise amplifiers, oscillators, detectors, and mixers. Design, fabrication, and measurements of wire antennas and arrays. Instructor: Antsos.

CS/CNS/EE 154. Artificial Intelligence. *9 units (3-3-3).* For course description, see Computer Science.

CS/CNS/EE 155. Probabilistic Graphical Models. *9 units (3-3-3).* For course description, see Computer Science.

CS/CNS/EE 156 ab. Learning Systems. *9 units (3-0-6).* For course description, see Computer Science.

EE/Ae 157 ab. Introduction to the Physics of Remote Sensing. *9 units (3-0-6); first, second terms. Prerequisite: Ph 2 or equivalent.* An overview of the physics behind space remote sensing instruments. Topics include the interaction of electromagnetic waves with natural surfaces, including scattering of microwaves, microwave and thermal emission from atmospheres and surfaces, and spectral reflection from natural surfaces and atmospheres in the near-infrared and visible regions of the spectrum. The class also discusses the design of modern space sensors and associated technology, including sensor design, new observation techniques, ongoing developments, and data interpretation. Examples of applications and instrumentation in geology, planetology, oceanography, astronomy, and atmospheric research. Instructor: van Zyl.

CS/CNS/EE 159. Projects in Machine Learning and AI. *9 units (0-0-9).* For course description, see Computer Science.

EE 160. Communication-System Fundamentals. *9 units (3-0-6); second term. Prerequisite: EE 111.* Laws of radio and guided transmission, noise as a limiting factor, AM and FM signals and signal-to-noise ratio, sampling and digital transmission, errors, information theory, error correction. Emphasis will be on fundamental laws and equations and their use in communication-system designs, including voice, video, and data. Instructor: Hassibi.

EE 161. Wireless Communications. *9 units (3-0-6); third term. Prerequisite: EE 160.* This course will cover the fundamentals of wireless channels and channel models, wireless communication techniques, and wireless networks. Topics include statistical models for time-varying narrowband and wideband channels, fading models for indoor and outdoor systems, macro- and microcellular system design, channel access and spectrum sharing using TDMA, FDMA, and CDMA, time-varying channel capacity and spectral efficiency, modulation and coding for wireless channels, antenna arrays, diversity combining and multiuser detection, dynamic channel allocation, and wireless network architectures and protocols. Instructor: Hassibi.

EE 163 ab. Communication Theory. *9 units (3-0-6); second, third terms. Prerequisites: EE 111; ACM/EE 116 or equivalent.* Least mean square error linear filtering and prediction. Mathematical models of communication processes; signals and noise as random processes; sampling and quantization; modulation and spectral occupancy; intersymbol interference and synchronization considerations; signal-to-noise ratio and error probability; optimum demodulation and detection in digital baseband and carrier communication systems. Instructors: Ho, Quirk.

EE 164. Stochastic and Adaptive Signal Processing. *9 units (3-0-6); third term. Prerequisite: ACM/EE 116 or equivalent.* Fundamentals of linear estimation theory are studied, with applications to stochastic and adaptive signal processing. Topics include deterministic and stochastic least-squares estimation, the innovations process, Wiener filtering and spectral factorization, state-space structure and Kalman filters, array and fast array algorithms, displacement structure and fast algorithms, robust estimation theory and LMS and RLS adaptive fields. Instructor: Hassibi.

EE/BE 166. Optical Methods for Biomedical Imaging and Diagnosis. *9 units (3-1-5); first term. Prerequisite: EE 151 or equivalent.* Topics include Fourier optics, scattering theories, shot noise limit, energy transitions associated with fluorescence, phosphorescence, and Raman emissions. Study of coherent anti-Stokes Raman spectroscopy (CARS), second harmonic generation and near-field excitation. Scattering, absorption, fluorescence, and other optical properties of biological tissues and the changes in these properties during cancer progression, burn injury, etc. Specific optical technologies employed for biomedical research and clinical applications: optical coherence tomography, Raman spectroscopy, photon migration, acousto-optics (and opto-acoustics) imaging, two photon fluorescence microscopy, and second- and third-harmonic microscopy. Instructor: Yang.

EE 167. Data Compression. *9 units (3-0-6); third term. Prerequisite: EE/Ma 126 or instructor's permission.* An introduction to the basic results, both theoretical and practical, of data compression. Review of relevant background from information theory. Fixed model and adaptive Huffman and arithmetic codes. The Lempel-Ziv algorithm and its variants. Scalar and vector quantization, including the Lloyd-Max quantizers, and the generalized Lloyd algorithm. Transform coding. Karhuenen-Loeve and discrete cosine transforms. The bit allocation problem. Subband coding. Practical algorithms for image and video compression. Not offered 2010–11.

EE/APh 180. Solid-State Devices. *9 units (3-0-6); second term. Prerequisite: EE 45.* Starting with the phenomenological statement of physical processes, the operation of a device is derived from fundamental principles and the device's materials and design. Subjects include the motion of charge carriers in solids, equilibrium statistics, the electronic structure of solids, doping, nonequilibrium states, the pn junction, the junction transistor, the Schottky diode, the field-effect transistor, the light-emitting diode, and the photodiode. Instructor: Scherer.

CS/EE 181 abc. VLSI Design Laboratory. *12 units (3-6-3).* For course description, see Computer Science.

APh/EE 183. Physics of Semiconductors and Semiconductor Devices. *9 units (3-0-6).* For course description, see Applied Physics.

CS/EE 184 ab. Computer Architecture. *9 units (3-3-3).* For course description, see Computer Science.

EE/BE 185. MEMS Technology and Devices. *9 units (3-0-6); third term. Prerequisite: APh/EE 9 ab, or instructor's permission.* Micro-electro-mechanical systems (MEMS) have been broadly used for biochemical, medical, RF, and lab-on-a-chip applications. This course will cover both MEMS technologies (e.g., micro- and nanofabrication) and devices. For example, MEMS technologies include anisotropic wet etching, RIE, deep RIE, micro/nano molding and advanced packaging. This course will also cover various MEMS devices used in microsensors and actuators. Examples will include pressure sensors, accelerometers, gyros, FR filters, digital mirrors, microfluidics, micro total-analysis system, biomedical implants, etc. Instructor: Tai.

CNS/Bi/EE 186. Vision: From Computational Theory to Neuronal Mechanisms. *12 units (4-4-4).* For course description, see Computation and Neural Systems.

EE 187. VLSI and ULSI Technology. *9 units (3-0-6); first term. Prerequisites: APh/EE 9 ab, EE/APh 180 or instructor's permission.* This course is designed to cover the state-of-the-art micro/nanotechnologies for the fabrication of ULSI including BJT, CMOS, and BiCMOS. Technologies include lithography, diffusion, ion implantation, oxidation, plasma deposition and etching, etc. Topics also include the use of chemistry, thermal dynamics, mechanics, and physics. Not offered 2010–11.

CNS/CS/EE 188. Topics in Computation and Biological Systems. *9 units (3-0-6).* For course description, see Computation and Neural Systems.

BE/EE 189 ab. Design and Construction of Biodevices. *12 units (3-6-3) first term; 9 units (0-9-0) second term.* For course description, see Bioengineering.

EE 226. Advanced Information and Coding Theory. *9 units (3-0-6); first term.* A selection of topics in information theory and coding theory not normally covered in EE/Ma 126 ab or EE/Ma/CS 127. These topics include constrained noiseless codes, constructive coding theorems for erasure channels, density evolution, repeat-accumulate and related codes, and network coding. Not offered 2010–11.

EE 243 abc. Quantum Electronics Seminar. *6 units (3-0-3); first, second, third terms.* Advanced treatment of topics in the field of quantum electronics. Each weekly seminar consists of a review and discussion of results in the areas of quantum electronics and optoelectronics. Instructor: Yariv.

CS/EE 245. Special Topics in Networking. *9 units (3-3-3).* For course description, see Computer Science.

CS/CNS/EE 253. Special Topics in Machine Learning. *9 units (3-3-3).* For course description, see Computer Science.

EE 291. Advanced Work in Electrical Engineering. *Units to be arranged.* Special problems relating to electrical engineering. Primarily for graduate students; students should consult with their advisers.

ENERGY SCIENCE AND TECHNOLOGY

EST/EE/ME 109 ab. Energy. *9 units (3-0-6); first, second terms. Prerequisites: Ph 1 abc and Ma 2 ab.* Modeling and forecasting. Heating, transportation, and electricity demand. Historical energy sources: wood and whale oil. Fossil-fuel supplies: oil, natural gas, coal, oil sands, and oil shale. Alternative energy sources: hydroelectric, nuclear, wind, biomass, geothermal, biofuels, waves, ocean thermal, solar photovoltaic, and solar thermal. Thermodynamics of energy conversion: vapor power cycles, combustion, combined cycle, and fuel cells. Transportation systems: internal combustion engines, gas turbines, and electric vehicles. Energy systems: pipelines, rail and water transport, shipping, carbon capture and sequestration, transmission lines and electricity distribution networks. Energy policy: efficiency regulations, biofuels vs food, water impacts, air pollution, and climate. Instructors: Rutledge, Shepherd.

MS/EST 143. Solid-State Electrochemistry for Energy Storage and Conversion. *9 units (3-0-6).* For course description, see Materials Science.

EST/MS/ME 199. Special Topics in Energy Science and Technology. *Units to be arranged.* Subject matter will change from term to term depending upon staff and student interest, but will generally center on modes of energy storage and conversion. Instructor: Staff.

ENGINEERING (GENERAL)

E 2. Frontiers in Engineering and Applied Science. *1 unit; first term. Open for credit to freshmen and sophomores.* Weekly seminar by a member of the EAS faculty to discuss his or her area of engineering and group's research at an introductory level. The course can be used to learn more about different areas of study within engineering and applied science. Graded pass/fail. Instructor: Rosakis.

E 10. Technical Seminar Presentations. *3 units (1-0-2); first, second, third terms. (Seniors required to take E 10 are given priority in registration. NOTE: Those who neither preregister nor attend the organizational meeting may not be permitted to enroll.)* Guidance and practice in organizing and preparing topics for presentation and in speaking with the help of visual aids, including whiteboards, overhead projectors, and video projectors. Instructor: Fender.

E 11. Written Technical Communication in Engineering and Applied Science. *3 units (1-0-2); second, third terms.* This class provides the opportunity for students to gain experience in technical writing in engineering and applied science. Students will choose a technical topic of interest, possibly based on a previous research or course project, and write a paper in a form that would be appropriate as an engineering report, a technical conference paper, or a peer-reviewed journal paper. The topic of ethical considerations for engineers and scientists as they arise in the publication and peer review process will also be discussed. A Caltech faculty member, a postdoctoral scholar, or technical staff member serves as a technical mentor for each student, to provide feedback on the content and style of the report. *Fulfills the Institute scientific writing requirement.* Instructors: Pierce, Readhead.

E 102. Entrepreneurial Development. *9 units (3-0-6); second term.* An introduction to the basics of getting a high-technology business started, including early-stage patent, organizational, legal, and financing issues; growing a company; taking a company public; and mergers and acquisitions. Lectures include presentations by invited experts in various specialties and keynote guest lecturers of national stature in technology start-ups. Instructor: Pickar.

E/ME 103. Management of Technology. *9 units (3-0-6); third term.* A course intended for students interested in learning how rapidly evolving technologies are harnessed to produce useful products. Students will work through Harvard Business School case studies, supplemented by lectures to elucidate the key issues. There will be a term project. The course is team-based and designed for students considering working in companies (any size, including start-ups) or eventually going to business school. Topics include technology as a growth agent, financial fundamentals, integration into other business processes, product development pipeline and portfolio management, learning curves, risk assessment, technology trend methodologies (scenarios, projections), motivation, rewards and recognition. Industries considered will include electronics (hardware and software), aerospace, medical, biotech, etc. E 102 and E/ME 105 are useful but not required precursors. Instructor: Pickar.

E/ME 105. Product Design for the Developing World. *9 units (3-0-6); first term.* The course will emphasize products appropriate for the developing world—for those people subsisting on less than one dollar a day. The focus is on Guatemala and taught in partnership with Landivar University in Guatemala City and the Art Center College of Design in Pasadena. The class consists of mixed teams, with lectures teleconferenced between countries. The class teaches product design methodologies informed by the special circumstances of the end customers. Technologies chosen are typically indigenous not "high tech". Issues of sustainability in a business as well as in an engineering sense are included as are cultural concerns, ultra low cost, manufacturability and ergonomic design. Each team works on a product which addresses people's basic needs, e.g., potable water, clean burning stoves, food processing, ergonomic carriers. Instructor: Pickar.

E 150 abc. Engineering Seminar. *1 unit; each term.* All candidates for the M.S. degree in applied mechanics, electrical engineering, materials science, and mechanical engineering are required to attend any graduate seminar in any division each week of each term. Graded pass/fail. Instructor: Fultz.

ENGLISH

En 1 a. English Composition for ESL Writers. *9 units (3-0-6 or 4-0-5); first term.* An introduction to English composition for students whose first language is not English and who need focused instruction before taking a freshman humanities course. This course offers fundamental strategies for composing fluent standard written English and for constructing academic arguments. Students are assigned to En 1 a based on a writing assessment that is required of all incoming students. *Not available for credit toward the humanities–social science requirement.* Instructor: Youra.

En 1 b. English Composition for ESL Writers. *9 units (3-0-6 or 4-0-5); offered by announcement.* Continuation of En 1 a for students who need additional instruction before taking a freshman humanities course. *Not available for credit toward the humanities–social science requirement.* Instructor: Staff.

En 2. Introduction to College Writing. *9 units (2-2-5); first term.* A course in developing forceful academic essays, for students who need more focused attention to writing before entering freshman humanities courses. It emphasizes analytic and argumentative writing and critical reading. The class features small seminar discussions and weekly conferences with the instructor. Students are assigned to En 2 based on a writing assessment that is required of all incoming students. *Not available for credit toward the humanities–social science requirement.* Instructors: Youra, Daley.

Hum/En 5. Major British Authors. *9 units (3-0-6).* For course description, see Humanities.

Hum/En 6. American Literature and Culture. *9 units (3-0-6).* For course description, see Humanities.

Hum/En 7. Modern European Literature. *9 units (3-0-6).* For course description, see Humanities.

F/En 30. Introduction to Film. *9 units (3-0-6).* For course description, see Film.

En 84. Writing About Science. *9 units (3-0-6); offered by announcement.* Instruction and practice in writing about science and technology for general audiences. The course considers how to convey complex technical information in clear, engaging prose that nonspecialists can understand and appreciate. Readings in different genres (e.g., magazine and newspaper journalism, reflective essays, case studies, popularizations) raise issues for discussion and serve as models for preliminary writing assignments and for a more substantial final project on a topic of each student's choice. Includes oral presentation. *Satisfies the Institute scientific writing requirement and the option oral communication requirement for humanities majors.* Instructor: Youra.

En 85. Writing Poetry. *9 units (3-0-6); third term.* Students will develop their poetic craft by creating poems in a variety of forms. The lecturer will provide guidance and direction, supervise class discussions of students' works, and assign outside reading as needed. Students may apply one term of En 85, 86, 87, and 88 to the additional HSS requirements, and all other courses in this series will receive Institute credit. Instructor: Hall.

En 86. Fiction and Creative Nonfiction Writing. *9 units (3-0-6); second term.* The class is conducted as a writing workshop in the short-story and personal essay/memoir form. Modern literary stories and essays are discussed, as well as the art and craft of writing well, aspects of "the writing life," and the nature of the publishing world today. Students are urged to write fiction or nonfiction that reflects on the nature of life. Humor is welcome, although not genre fiction such as formula romance, horror, thrillers, fantasy, or sci-fi. Students may apply one term of En 85, 86, 87, 88, and 89 to the additional HSS requirements, and all other courses in this series will receive Institute credit. Instructor: Gerber.

En 87. Writing Fiction: The Imaginary. *9 units (3-0-6); third term.* Students will develop their talents for writing imaginary short stories other than science fiction. A number of models will be proposed to them for inspiration, e.g., folk tales, tales of the supernatural, fables, stories of "magic realism," examples of surrealism and the "absurd," and so on. The lecturer will provide guidance and direction, supervise class discussions of students' works, and assign outside reading as needed. Students may apply one term of En 85, 86, 87, 88, and 89 to the additional HSS requirements, and all other courses in this series will receive Institute credit. Not offered 2010–11.

En 88. Memoir: Writing the Self. *9 units (3-0-6); second term.* Whereas a diarist writes from an ever-moving present, the art of memoir demands remembering, standing far enough back to shape experience and give it meaning, to discover a "story line" one never suspected existed, to find continuity in seeming randomness. Students may apply one term of En 85, 86, 87, 88, and 89 to the additional HSS requirements, and all other courses in this series will receive Institute credit. Not offered 2010–11.

En 89. News Writing. *9 units (3-0-6).* This course teaches the basic skills of news gathering and reporting. Students learn how to research stories, conduct interviews, structure news articles, and produce balanced copy. They also work on developing concise and effective prose. In addition to writing several articles, assignments include reading and discussing material from professional newspapers as well as analyzing and editing the writing of peers. The course covers other topics relevant to responsible news writing, such as journalistic ethics, the tradition and responsibilities of free speech, and the social function of the press in a democracy. Affiliation with the *California Tech* is not a requirement for enrollment. Students may apply one term of En 85, 86, 87, 88, and 89 to the additional HSS requirements, and all other courses in this series will receive Institute credit. Not offered 2010–11.

En 92. Literature of the Holocaust. *9 units (3-0-6); third term.* Elie Wiesel has written: "At Auschwitz, not only man died, but also the idea of man . . . It was its own heart the world incinerated at Auschwitz." This class will explore the reverberation of this premise in the literature that grew out of the holocaust experience, as well as the shifting aesthetics of "holocaust literature" over the last half century. Put simply, can there be "an aesthetics of atrocity"? What are the responsibilities of art and literature to history? Should a perpetrator of genocide ever engage our moral imagination? In an attempt to grapple with these questions, students will read works, both fiction and nonfiction, by a range of authors, including Primo Levi, Elie Wiesel, Ida Fink, Cynthia Ozick, Tadeusz Borowski, Bernard Schlink, and W. G. Sebold. Not offered 2010–11.

En 93. Women on the Edge. *9 units (3-0-6); third term.* This class will consider how women's writing in the 20th century often flouts the conventional portrayal of woman as ministering angel preoccupied with the needs of family without much regard to her own. Writers to be read include Kate Chopin, Colette, Marguerite Duras, Sylvia Plath, Angela Carter, Jeanette Winterson, Toni Morrison, Elfriede Jelinek. Not offered 2010–11.

En 98. Reading in English. *9 units (1-0-8). Prerequisite: instructor's permission.* An individual program of directed reading in English or American literature, in areas not covered by regular courses. Instructor: Staff.

En 99 ab. Senior Tutorial for English Majors. *9 units (1-0-8).* Students will study research methods and write a research paper. Required of students in the English option. Instructor: Staff.

En 113 ab. Shakespeare's Career. *9 units (3-0-6).* A survey of Shakespeare's career as a dramatist. The first term will study his comedies and histories; the second, his tragedies and tragicomedies. Students will need to read one play per week. Instructor: Pigman.

En 114 ab. Shakespeare. *9 units (3-0-6); second term.* A close study of Shakespeare's plays with an emphasis on his language, dramatic structures, characters, and themes. Each term will concentrate on a detailed consideration of three or four of Shakespeare's major plays. The first term is not a prerequisite for the second. Not offered 2010–11.

En 116. Milton and the Epic Tradition. *9 units (3-0-6); third term.* Epic poetry is a competitive and self-referential genre. Virgil imitates and revises Homer, Dante makes Virgil his guide through hell and most of purgatory before leaving him behind, and Milton transforms the entire epic tradition. Since Milton's engagement with and criticism of the epic are essential elements of *Paradise Lost and Paradise Regained*, we will focus on his dialogue with Homer, Virgil, and Dante and their differing conceptions of heroism. Not offered 2010–11.

En 119. Displacement. *9 units (3-0-6); third term.* The literary fascination with people who change places, temporarily or permanently, over a short distance or across the globe, in works dating from our lifetimes and from the recent and the remote past. How readily can such stories be compared, how easy is it to apply traditional categories of literary evaluation, and, in the contemporary world, how have poetry and prose fictions about migration survived alongside other media? 21st-century works will receive considerable attention; other readings may include Virgil, Swift, Flaubert, Mann, Achebe, Nabokov, Didion, Morrison. Not offered 2010–11.

En 120. Books. *9 units (3-0-6).* This class examines not only the long history of book production in the West, but also the multifarious uses to which books have been put. Historical topics might include political advice manuals (Machiavelli), prophecies of world destruction (Nostradamus), and the cult of the national author (beginning with Shakespeare's fans in the 17th and 18th centuries); closer to our time, potential topics include scientific books that also became best sellers (Darwin and Freud), metafictions, and the rise of the book club. The emphasis is on the circulation of books as physical objects. Not offered 2010–11.

En 121. Literature and Its Readers. *9 units (3-0-6); first term.* The course will investigate readers who have made adventurous uses of their favorite works of literature, from Greek antiquity through the 20th century. Sometimes those readers count, at least temporarily, as literary critics, as when the philosopher Aristotle made Sophocles' *Oedipus the King* the central model in his wildly successful essay on the literary form of tragedy. Other readers have been even more experimental, as when Sigmund Freud, studying the same play, made the "Oedipus complex" a meeting point for his theory of psychology, his vision of human societies, and his fascination with literary narrative. It will discuss some basic questions about the phenomenon of literary reading. Does a book have a single meaning? Can it be used rightly or wrongly? Instructor: Haugen.

En 122. Early History of the Novel. *9 units (3-0-6); third term.* The realistic novel is a surprising, even experimental moment in the history of fiction. How and why did daily life become a legitimate topic for narrative in the 18th century? The realistic turn clearly attracted new classes of readers, but did it also make the novel a better vehicle for commenting on society at large? Why were the formal conventions of realistic writing so tightly circumscribed? Authors may include Cervantes, Defoe, Richardson, Fielding, Sterne, Walpole, Boswell, and Austen. Not offered 2010–11.

En 123. The 19th-Century English Novel. *9 units (3-0-6); third term.* A survey of the 19th-century novel from Austen through Conrad, with special emphasis upon the Victorians. Major authors may include Austen, Shelley, Dickens, Eliot, Thackeray, Gaskell, Brontë, Collins, Trollope, Stoker, Hardy. Instructor: Gilmore.

En 124. 20th-Century British Fiction. *9 units (3-0-6); third term.* A survey of the 20th-century British and Irish novel, from the modernist novel to the postcolonial novel. Major authors may include Conrad, Joyce, Woolf, Forster, Lawrence, Orwell, Amis, Lessing, Rushdie. Not offered 2010–11.

En 125. British Romantic Literature. *9 units (3-0-6); second term.* A selective survey of English writing in the late 18th and early 19th centuries. Major authors may include Blake, Wordsworth, Coleridge, Byron, Keats, Percy Shelley, Mary Shelley, and Austen. Particular attention will be paid to intellectual and historical contexts and to new understandings of the role of literature in society. Instructor: Gilmartin.

En 126. Gothic Fiction. *9 units (3-0-6); third term.* The literature of horror, fantasy, and the supernatural, from the late 18th century to the present day. Particular attention will be paid to gothic's shifting cultural imperative, from its origins as a qualified reaction to Enlightenment rationalism, to the contemporary ghost story as an instrument of social and psychological exploration. Issues will include atmosphere and the gothic sense of space; gothic as a popular pathology; and the gendering of gothic narrative. Fiction by Walpole, Shelley, Brontë, Stoker, Poe, Wilde, Angela Carter, and Toni Morrison. Film versions of the gothic may be included. Instructor: Gilmartin.

En 128. Modern and Contemporary Irish Literature. *9 units (3-0-6); offered by announcement.* The development of Irish fiction, poetry, and drama from the early 20th-century Irish literary renaissance, through the impact of modernism, to the Field Day movement and other contemporary developments. Topics may include the impact of political violence and national division upon the literary imagination; the use of folk and fairy-tale traditions; patterns of emigration and literary exile; the challenge of the English language and the relation of Irish writing to British literary tradition; and recent treatments of Irish literature in regional, postcolonial, and global terms. Works by Joyce, Yeats, Synge, Friel, O'Brien, Heaney, Boland, and others. Not offered 2010–11.

En 129. Enlightenment Fiction. *9 units (3-0-6); third term.* What was the fate of fiction in an Age of Reason? Historians have questioned whether a conventional sense of the Enlightenment adequately accounts for European culture in the 18th century, and the literary imagination can seem particularly unsuited to generalizations about progress, optimism, reason, and social order. This course will consider experimental narratives and philosophical satires from the English and Continental tradition, as well as early Romantic responses to the Enlightenment. Readings may include Defoe, Sterne, Voltaire, Diderot, Mary Shelley, Hoffman, and fairy tales from the brothers Grimm. Not offered 2010–11.

En 130. Vital Signs: Literature and the Human Body. *9 units (3-0-6)*. A literary history of the human body, from the Renaissance to the present. Often overlooked in intellectual life, our bodies nevertheless play a crucial role in our everyday mental, emotional, and social experience. But the language of the body is difficult to read. With the aid of thinkers from Plato to Marx and Freud, as well as film and drama, students will explore the significance of the body through a wide range of poetry and fiction. We will consider the following questions: What can literature teach us about the body that science cannot? How does literature represent and communicate bodily experience? What is the relation between writing and performative arts such as singing and dancing, religious rituals, or sport? What is the fate of the body in a technologically advanced culture such as ours? Authors studied may include Shakespeare, Coleridge, Wordsworth, Mary Shelley, Keats, Dickinson, Whitman, Melville, Stein, Hughes, and Levi. Not offered 2010–11.

En 131. Poe's Afterlife. *9 units (3-0-6).* This course focuses on Edgar Allan Poe and the considerable influence his works have had on other writers. Authors as diverse as Charles Baudelaire, Jules Verne, Jorge Luis Borges, Vladimir Nabokov, John Barth, and Philip Roth have used Poe's stories as departure points for their own work. We shall begin by reading some of Poe's s classic short stories, including "The Narrative of Arthur Gordon Pym," "The Purloined Letter," and others. We shall then explore how and why Poe's stories have been so important for authors, despite the fact that his reputation as a great American writer, unlike Hawthorne's and Melville's, for example, is a relatively recent phenomenon. Not offered 2010–11.

En 132. American Literature Until the Civil War. *9 units (3-0-6); third term.* The course will analyze the literature of this period, from the Puritans through Melville, to determine how various writers understood their relationship to a new world of seemingly unlimited possibility. Authors covered may include Mary Rowlandson, Benjamin Franklin, Hannah Foster, Harriet Jacobs, Emerson, Thoreau, Harriet Beecher Stowe, Hawthorne, and Melville. Instructor: C. Hunter.

En 133. 19th-Century American Women Writers. *9 units (3-0-6), second term.* This course will analyze many of the most popular novels written in the 19th century. How might we account for their success in the 19th century and their marginalization (until recently) in the 20th century? Why were so many of these texts "sentimental"? How might we understand the appeal of "sentimental" literature? What are the ideological implications of sentimentalism? Authors may include Stowe, Warner, Cummins, Alcott, Phelps, Fern, etc. Not offered 2010–11.

En 134. The Career of Herman Melville. *9 units (3-0-6), first term.* The course will focus on Melville's works from *Typee* through *Billy Budd*. Special emphasis will be placed on Melville's relations to 19th-century American culture. Not offered 2010–11.

En 136. The Fiction of Charles Dickens. *9 units (3-0-6).* An overview of the Great Inimitable's fiction, concentrating on four texts representative of different phases of his novel-writing career and their relationship to the changing world of Victorian Britain: *Oliver Twist*, *Dombey and Son*, *Bleak House*, *Our Mutual Friend.* Not offered in 2010–11.

En 137. African American Literature. *9 units (3-0-6); second term.* This course analyzes some of the great works of American literature written by African Americans. This body of writing gives rise to two crucial questions: How does African American literature constitute a literary tradition of its own? How is that tradition inextricable from American literary history? From slave narratives to Toni Morrison's *Beloved*, from the Harlem Renaissance to Alice Walker, from Ralph Ellison to Walter Mosley, African American literature has examined topics as diverse and important as race relations, class identification, and family life. We shall analyze these texts not only in relation to these cultural issues, but also in terms of their aesthetic and formal contributions. Not offered 2010–11.

En 138. Twain and His Contemporaries. *9 units (3-0-6); third term.* This course will study the divergent theories of realism that arose in the period after the Civil War and before World War I. Authors covered may include Howells, James, Charlotte Perkins Gilman, Twain, Sarah Orne Jewett, Jacob Riis, Stephen Crane, and W. E. B. DuBois. Not offered 2010–11.

En 141. James and Wharton. *9 units (3-0-6); third term.* The course covers selected novels, short fiction, and nonfiction writings of friends and expatriates Henry James and Edith Wharton. It will consider formal questions of style and genre as well as the literature's preoccupation with describing and defining American modernity, despite the authors' shared ambivalence toward their native country. Students will read as many as, but no more than, five novels. Texts covered may include *The Portrait of a Lady*, *Daisy Miller*, *The Ambassadors*, selections from *The Decoration of Houses*, *The House of Mirth*, *The Custom of the Country*, and *The Age of Innocence*. Not offered 2010–11.

En 145. American Ethnic Literature and the Drama of Assimilation. *9 units (3-0-6).* From the idea of the melting pot to contemporary debates about multiculturalism, ideas about assimilation have been crucial to understanding what it means to be American. As a nation of immigrants, the United States has produced countless narratives that describe the struggles of newcomers to adapt to an alien culture while they are also trying to negotiate a meaningful relation to their native culture. We will be reading novels, autobiographies, sociology, and other texts that address the meaning of assimilation and consider the costs, benefits, and the very possibility of joining the cultural mainstream. Not offered 2010–11.

En 148. Modern American Poetry. *9 units (3-0-6); first term.* A study of modern American poetry in its historical and literary context. Exploring some of the most innovative and difficult writing in the English language, this course confronts the startling range of poetic composition in the United States in the 20th century. Poets studied will include T. S. Eliot, Ezra Pound, Gertrude Stein, William Carlos Williams, Robert Frost, Wallace Stevens, Mina Loy, Marianne Moore, Langston Hughes, and Allen Ginsberg, among others. Not offered 2010–11.

En 150. Fundamentals of the Art of Poetry. *9 units (3-0-6); first term.* What is poetry? Why and how should one read it? What "weapons" does the good poem deploy in order to give pleasure? How does an inexperienced reader develop into an expert and a sensitive one? To illustrate the nature, functions, and resources of poetry, a wide-ranging selection of poems will be read and discussed. Not offered 2010–11.

En/F 160 ab. Introduction to Classical Hollywood Film. *9 units (3-0-6); second, third terms.* This course introduces students to Hollywood films and filmmaking during the classical period, from the coming of sound through the '50s. It will cover basic techniques and vocabulary of film analysis, as we learn to think of films as texts with distinctive formal properties. Topics include the rise and collapse of the studio system, technical transformations (sound, color, deep focus), genre (the musical, the melodrama), cultural contexts (the Depression, World War II, the Cold War), audience responses, and the economic history of the film corporations. Terms may be taken independently. Part a covers the period 1927–1940. Part b covers 1941–1960. Instructor: Jurca.

En 170. Drama from the Middle Ages to Molière. *9 units (3-0-6); third term.* A study of major dramatic works from the 15th to the mid-17th century. Students will read medieval plays like Abraham and Isaac and Everyman; British Renaissance works including Marlowe's Doctor Faustus and two Shakespearean plays; several Spanish comedias of the Golden Age, among them the original Don Juan play; and Molière's masterpieces: *Tartuffe* and *The Misanthrope.* Not offered 2010–11.

En 171. Drama from Molière to Wilde. *9 units (3-0-6), third term.* A study of French plays of the age of Louis XIV, featuring Molière and Racine; English comedies of the 17th and 18th centuries, including Sheridan's *The Rivals;* masterpieces of German drama of the Romantic age, among them Schiller's *Maria Stuart* and Goethe's *Faust; The Inspector General* by the Russian Nikolay Gogol; Edmond Rostand's

Cyrano de Bergerac; Oscar Wilde's *The Importance of Being Earnest*, and other works as time permits. Not offered 2010–11.

En 172. Drama from Ibsen to Beckett. *9 units (3-0-6); second term.* A wide international range of plays will be studied, beginning with major texts by Ibsen and Chekhov, and concluding with Ionesco and Beckett. In between, students will read important plays by G. B. Shaw, Sean O'Casey, Pirandello, Bertolt Brecht, T. S. Eliot, Arthur Miller, and others. Not offered 2010–11.

En 180. Special Topics in English. *9 units (3-0-6). See registrar's announcement for details.* Instructor: Staff.

En 181 a. Classics of Science Fiction: 1940–70. *9 units (3-0-6); third term.* This course will aim to examine, critically, the achievements of one of the many "golden ages" of science fiction. Among the authors examined will be Pohl and Kornbluth, Bradbury, Bester, Vonnegut, Wyndham, Heinlein, Dick, Herbert, Ballard, Le Guin, Asimov, Clarke, Silverberg, Aldiss. The course will aim to give formal and generic definition to the texts examined and to reinsert them into the period of their original publication. Not offered 2010–11.

En 181 b. Hardy: The Wessex Novels. *9 units (3-0-6); third term.* This course will examine the body of work that the late Victorian novelist Thomas Hardy published under the general title *The Wessex Novels*, that is, the sequence of works from *Far from the Madding Crowd* to *Jude the Obscure*. The six main novels will be read critically to give a sense of the totality of this greatest British regional novelist's achievement. Not offered 2010–11.

En 181 c. Classics of Science Fiction: The 1960s. *9 units (3-0-6); third term.* This course will aim to examine critically the achievements of one of the many "golden ages" of science fiction. Among the authors dealt with (but not necessarily restricted to) in the course will be Pohl and Kornbluth, Bester, Dick, Asimov, Clarke, Aldiss, Ballard, Le Guin, Wyndham. The course will aim to give formal and generic definition to the texts covered and to reinsert them into the period of their original conception and publication. Not offered 2010–11.

En 181 d. Jane Austen, Our Contemporary. *9 units (3-0-6); first term.* This course will examine in sequence, and in depth, the major novels of Jane Austen: *Northanger Abbey*, *Sense and Sensibility*, *Pride and Prejudice*, *Emma*, *Mansfield Park*, and *Persuasion*. In addition to intensive reading, attention will be given to the many adaptations of Austen's novels in other media. Not offered 2010–11.

En 181 e. Dickens and the Dickensian. *9 units (3-0-6).* The adjective "Dickensian" makes an almost daily appearance in today's newspapers, magazines, and other media sources. It is used to describe everything from outrageous political scandals, to Bollywood musicals, to multiplot novels. But what does the word really mean? And what part of

Charles Dickens's output does it refer to? This class will consider some of Dickens's most famous works alongside a series of contemporary novels, all critically described in "Dickensian" terms. The main concern will be equally with style and form, and 19th-century and present-day circumstances of production (e.g., serialization, mass production, Web publication, etc.). Authors considered (aside from Dickens) may include Richard Price, Zadie Smith, Monica Ali, and Jonathan Franzen. Not offered 2010–11.

En 182. Literature and the First Amendment. *9 units (3-0-6); second term.* "Freedom of speech," writes Benjamin Cardozo in *Palko v. Connecticut* (1937), "is the matrix, the indispensable condition, of nearly every other form of freedom." We will go inside the matrix, focusing on how it has affected the books we read. This is not a course in constitutional law or political philosophy, but an opportunity to examine how American literary culture has intersected with law and politics. We will investigate the ways in which the meanings of "freedom," what it entails, and who is entitled to it have changed over time. Possible topics include the obscenity trials surrounding Allen Ginsberg's *Howl* and James Joyce's *Ulysses*, crackdowns on anti-war propagandists, and the legal battle between *Hustler* publisher Larry Flynt and televangelist and Moral Majority cofounder Jerry Falwell. Instructor: C. Hunter.

En 183. Victorian Crime Fiction. *9 units (3-0-6); first term.* In 19th-century Britain, for the first time in human history, more of a nation's citizens came to live in urban areas than in rural ones. This result of the Industrial Revolution produced many effects, but in the fiction of the period, one of the most striking was an obsession with the problem of crime. Victorian authors filled their novels with murder, prisons, poisonings, prostitution, criminals, and the new figure of the detective; in this class we will look at the social history, publishing developments, and formal dilemmas that underlay such a response. Authors studied may include Dickens, Collins, Braddon, Conan Doyle, Chesterton, and Conrad, among others. Instructor: Gilmore.

En 184. Literary Biography. *9 units (3-0-6); third term.* This course is devoted to *The Life of Samuel Johnson* (1791), one of the strangest biographies and indeed one of the strangest books in English literature. Johnson, a respected poet and the best-known critic of his time, was also famous for editing Shakespeare, publishing biographies of earlier poets, and compiling a mammoth dictionary of English. James Boswell, his much younger admirer, obsessively recorded Johnson's conversation and gathered documents of his life in an effort to produce a real, unvarnished, and unprecedented kind of biography. In addition to *The Life*, we examine some of Johnson's own works, poetry by other contemporaries, Boswell's diaries, and other relevant sources. The aim is to understand the literary culture of eighteenth-century England by means of one focused and particularly rich case study. Instructor: Haugen.

ENGLISH AS A SECOND LANGUAGE

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Please see pages 238–239 for requirements regarding English competency. All of the following courses are open to international graduate students only.

ESL 101 ab. Oral Communication and Pronunciation. *3 units (3-0-0); offered by announcement.* Communication and pronunciation in spoken English. Development of pronunciation, vocabulary, listening comprehension, and accuracy and fluency in speaking. Aspects of American culture will be discussed. The first term is required for all first-year international students designated by the ESL screening process. Passing the class is based on attendance and effort. Graded pass/fail.

ESL 102. Advanced Spoken English for Academic Purposes. *Noncredit; offered by announcement.* Development of fluency and communication strategies. Emphasis on presentation skills and interpersonal communication on scientific topics. Strongly recommended for first-time international graduate teaching assistants.

ESL 103. English in Everyday Life. *Noncredit; offered by announcement.* Expressions, vocabulary, slang, and idioms used in daily life. Conversation and discussion, with feedback from instructors. Occasional grammar and pronunciation review. Comprehension of newspaper and magazine articles, as well as films and television programs.

ESL 104. Pronunciation Improvement and Accent Reduction. *Noncredit; offered by announcement.* Aspects of American English pronunciation. Vowels and consonants, word and syllable stress, sentence stress and rhythm, intonation, and linking. Intensive practice and techniques for achieving correct pronunciation through self-monitoring.

ESL 105. Oral Presentation and Public Speaking. *Noncredit; offered by announcement.* Oral presentation in a variety of settings, including oral exams, seminars, conferences, and the classroom. Focus on the organization of ideas, delivery techniques, pronunciation, grammar, and vocabulary. Frequent in-class presentations by students based on their current research interests, followed by critiques. Improvement of confidence and delivery skills.

ESL 106. Writing Seminar. *Noncredit; offered by announcement.* Strategies for improving academic writing. Emphasis on grammar, word choice, organization, logical connectors, and punctuation. Classroom exercises and editing practice based on student writing samples.

ESE 1. Introduction to Environmental Science and Engineering. *9 units (3-0-6); third term. Prerequisites: Ph 1 ab, Ch 1 ab, and Ma 1 ab.* An introduction to the array of major scientific and engineering issues related to environmental quality on a local, regional, and global scale. Fundamental aspects of major environmental problems will be addressed with an overall focus on the dynamic interplay among the atmosphere, biosphere, geosphere, and hydrosphere. Underlying scientific principles based on biology, chemistry, and physics will be presented. Engineering solutions to major environmental problems will be explored. Not offered on a pass/fail basis. *Satisfies the menu requirement of the Caltech core curriculum.* Not offered 2010–11.

ESE 90. Undergraduate Laboratory Research in Environmental Science and Engineering. *Units by arrangement; any term. Approval of research supervisor required prior to registration.* Independent research on current environmental problems; laboratory or field work is required. A written report is required for each term of registration. Graded pass/fail. Instructor: Staff.

ESE 100. Special Topics in Environmental Science and Engineering. *6 or more units as arranged. Prerequisite: instructor's permission.* Special courses of reading, problems, or research for first-year graduate students or qualified undergraduates. Graded pass/fail. Instructor: Staff.

ESE 101. Current Problems in Environmental Science and Engineering. *3 units; first term.* A discussion course that focuses on current research by ESE faculty, and open research questions in the field. Required for first-year ESE graduate students. Instructor: Wennberg.

ACM/ESE 118. Methods in Applied Statistics and Data Analysis. *9 units (3-0-6).* For course description, see Applied and Computational Mathematics.

ESE 142. Aquatic Chemistry. *9 units (3-0-6); first term. Prerequisite: Ch 1 or instructor's permission.* Principles of inorganic and physical chemistry applied to natural and engineered aquatic systems. Biogeochemical processes controlling the major ion composition of aquatic systems and the behavior of the trace inorganic constituents of such systems are examined. Fundamental aspects of thermodynamics and quantitative description of the composition of natural waters are stressed. Instructor: Adkins.

Ge/ESE 143. Organic Geochemistry. *9 units (3-2-4).* For course description, see Geological and Planetary Sciences.

Ge/ESE 145. Isotopic Biogeochemistry Seminar. *6 units (3-0-3).* For course description, see Geological and Planetary Sciences.

ESE/Ge 148 abc. Global Environmental Science. *9 units each term. Prerequisites: Ch 1, Ma 2, Ph 2, or equivalents.* Global change on timescales of years to centuries.

a. Climate Change. *(3-0-6); first term.* Radiative transfer and the greenhouse effect. Scattering and absorption by gases, clouds, and aerosols. Feedbacks due to water vapor, clouds, ice, and vegetation. Chemistry of greenhouse gases. Climates of the past. Ice ages. The global-warming debate. Economic and political aspects of climate change. Instructor: Wennberg.

b. Atmosphere-Ocean Circulations. *(3-0-6); second term.* Large-scale motions in Earth's atmosphere and oceans. Effects of planetary rotation and density stratification. Observing systems and data assimilation. Numerical weather prediction. Climate modeling. Parameterizations. Dynamical aspects of El Niño, global warming, and the ozone hole. Instructor: Bordoni.

c. Biogeochemical Cycles. *(3-0-6); third term.* Global biogeochemical cycles, fluxes, and reservoirs in the solid earth, oceans, biosphere, and atmosphere. The hydrologic cycle, weathering and erosion, soil formation, nutrient cycling and limitation, ecosystem function and metrics, photosynthesis and primary production, heterotropic recycling, carbon cycle dynamics, atmospheric trace gases, and stable-isotope tracers. Variability in biogeochemical cycles over Earth history, and recent modification by human activities. Instructor: Sessions.

Ge/ESE 149. Marine Geochemistry. *9 units (3-0-6).* For course description, see Geological and Planetary Sciences.

ESE 150 abc. Seminar in Environmental Science and Engineering. *1 unit; each term.* Seminar on current developments and research within the field of environmental engineering science, with special consideration given to work at the Institute. Graded pass/fail. Instructor: Wennberg.

ESE/Ge 152. Atmospheric Radiation. *9 units (3-0-6); third term. Prerequisite: ESE/Ge 148 a or instructor's permission.* The basic physics of absorption and scattering by molecules, aerosols, and clouds. Theory of radiative transfer. Band models and correlated-k distributions and scattering by cloud and aerosol particles. Solar insolation, thermal emission, heating rates, and applications to climate and remote sensing. Instructor: Yung.

ESE/Ge 153. Atmosphere and Climate Dynamics. *9 units (3-0-6); third term. Prerequisite: ESE 148 b or an introductory fluid dynamics course.* Introduction to the basic physical balances governing atmospheric circulations and climate. Topics include the angular momentum balance of the atmosphere and how it is maintained; the energy balance, heat transport, and the nature of the atmospheric heat engine; and the hydrologic cycle. The course gives an overview of the dominant processes that govern the surface climate, with a focus on phenomenology and order-of-magnitude physics that is applicable to climates generally, including those of Earth's distant past and of other planets. Not offered 2010–11.

Ge/ESE 154. Readings in Paleoclimate. *3 units (1-0-2).* For course description, see Geological and Planetary Sciences.

Ge/ESE 155. Paleoceanography. *9 units (3-0-6).* For course description, see Geological and Planetary Sciences.

ChE/ESE 158. Aerosol Physics and Chemistry. *9 units (3-0-6).* For course description, see Chemical Engineering.

ESE 159. Environmental Analysis Laboratory. *9 units (1-6-2); third term. Prerequisite: any 100-level ESE course or instructor's permission.* Introduction to modern laboratory techniques and basic sampling principles in environmental water, air, and biological analysis. Modular experiments will address sampling, measurement, and data analysis based around a region of local environmental interest. Regions may include the Arroyo Seco watershed, San Gabriel Mountains, or Caltech campus. Principles of basic experimental design, laboratory technique, elementary statistics, and scientific writing will be emphasized. Not offered 2010–11.

ESE/Bi 166. Microbial Physiology. *9 units (3-1-5); first term. Recommended prerequisite: one year of general biology.* A course on growth and functions in the prokaryotic cell. Topics covered: growth, transport of small molecules, protein excretion, membrane bioenergetics, energy metabolism, motility, chemotaxis, global regulators, and metabolic integration. Instructor: Leadbetter.

ESE/Bi 168. Microbial Metabolic Diversity. *9 units (3-0-6); second term. Prerequisites: ESE 142, ESE/Bi 166.* A course on the metabolic diversity of microorganisms. Basic thermodynamic principles governing energy conservation will be discussed, with emphasis placed on photosynthesis and respiration. Students will be exposed to genetic, genomic, and biochemical techniques that can be used to elucidate the mechanisms of cellular electron transfer underlying these metabolisms. Instructor: Leadbetter.

Ge/ESE 170. Microbial Ecology. *9 units (3-2-4).* For course description, see Geological and Planetary Sciences.

ESE/Ge/Ch 171. Atmospheric Chemistry I. *9 units (3-0-6); third term. Prerequisite: Ch 1 or equivalent.* A detailed course about chemical transformation in Earth's atmosphere. Kinetics, spectroscopy, and thermodynamics of gas-phase chemistry of the stratosphere and troposphere; sources, sinks, and lifetimes of trace atmospheric species; stratospheric ozone chemistry; oxidation mechanisms in the troposphere. Instructors: Seinfeld, Wennberg.

ESE/Ge/Ch 172. Atmospheric Chemistry II. *3 units (3-0-0); first term. Prerequisite: ESE/Ge/Ch 171 or equivalent.* A lecture and discussion course about active research in atmospheric chemistry. Potential topics include halogen chemistry of the stratosphere and troposphere; aerosol formation in remote environments; coupling of dynamics and photochemistry; development and use of modern remote-sensing and in situ instrumentation. Graded pass/fail. Not offered 2010–11.

ESE/Ge 173. Topics in Atmosphere and Ocean Dynamics. *9 units (3-0-6); third term. Prerequisite: ESE/Ge 153 or equivalent.* A lecture and discussion course on current research in atmosphere and ocean dynamics. Topics covered vary from year to year and may include global circulations of planetary atmospheres, geostrophic turbulence, atmospheric convection and cloud dynamics, wave dynamics and large-scale circulations in the tropics, large-scale ocean dynamics, and dynamics of El Niño and the Southern Oscillation. Instructor: Schneider.

ESE/Ch/Ge 175 ab. Environmental Organic Chemistry. *9 units (3-0-6); second, third terms.* A detailed analysis of the important chemical reactions and physicochemical processes governing the behavior and fate of organic compounds in the surface and subsurface aquatic environments. The course is focused on physical organic chemistry relevant to natural waters. Fundamental aspects of thermodynamics, kinetics, mechanisms, and transport are stressed. Instructor: Hoffmann.

ESE 200. Advanced Topics in Environmental Science and Engineering. *Units by arrangement, any term.* Course to explore new approaches to environmental problems. The topics covered vary from year to year, depending on the interests of the students and staff.

Ge/ESE/CE 226. Sediment Transport Mechanics and Morphodynamics. *9 units (3-0-6).* For course description, see Geological and Planetary Sciences.

ESE 300. Thesis Research.

For other closely related courses, see listings under Chemistry, Chemical Engineering, Civil Engineering, Mechanical Engineering, Biology, Geology, Economics, and Social Science.

Graduate students may also enroll in graduate courses offered by the Scripps Institution of Oceanography under an exchange program. Graduate students majoring in environmental science and engineering, who may take a subject minor in oceanography for the Ph.D. degree, should consult the executive officer for more information.

FILM

F/En 30. Introduction to Film. *9 units (3-0-6).* This course examines film as an art and as an institution from 1895 through the present. Students will acquire the basic vocabulary and techniques of film analysis, focusing on questions of form (mise-en-scène, cinematography, editing, sound) and narrative, as well as an understanding of the historical development of the medium with an emphasis on the American, European, and Asian contexts. Topics will include the early cinema of illusion, the actuality film, the transition to sound, the Hollywood star system, Italian neorealism, the French New Wave, Dogma 95, and Hong Kong action cinema. Not offered 2010–11.

F/Hum 32. Humanities on Film. *3 units (1-1-1); offered by announcement.* A course centered around a series of films (usually five) screened as part of the Caltech film program. Students will be required to attend prefilm lectures and postfilm discussions, to do some reading, and to produce a short paper.

L/F 104. French Cinema. *9 units (3-0-6).* For course description, see Languages.

L/F 109. Introduction to French Cinema from Its Beginning to the Present. *9 units (3-0-6).* For course description, see Languages.

H/F 131. History on Film. *9 units (2-2-5).* For course description, see History.

H/F 133. Topics in Film History. *9 units (2-2-5).* For course description, see History.

H/F 134. The Science Fiction Film. *9 units (2-2-5).* For course description, see History.

H/F 136. Ethnic Visions. *9 units (2-2-5).* For course description, see History.

En/F 160 ab. Introduction to Classical Hollywood Film. *9 units (3-0-6).* For course description, see English.

GEOLOGICAL AND PLANETARY SCIENCES

Geology, Geobiology, Geochemistry, Geophysics, Planetary Science

Ge 1. Earth and Environment. *9 units (3-3-3); third term.* An introduction to the ideas and approaches of earth and environmental sciences, including both the special challenges and viewpoints of these kinds of science as well as the ways in which basic physics, chemistry, and biology relate to them. In addition to a wide-ranging lecture-oriented component, there will be a required field trip component (two weekend days). The lectures and topics cover such issues as solid earth structure and evolution, plate tectonics, oceans and atmospheres, climate change, and the relationship between geological and biological evolution. Not offered on a pass/fail basis. Instructor: Wernicke. *Satisfies the menu requirement of the Caltech core curriculum.*

Ge 10. Frontiers in Geological and Planetary Sciences. *2 units (2-0-0); second term. The course may be taken multiple times.* Weekly seminar by a member of the Division of Geological and Planetary Sciences or a visitor to discuss a topic of his or her current research at an introductory level. The course is designed to introduce students to research and research opportunities in the division and to help students find faculty sponsors for individual research projects. Graded pass/fail. Instructors: Farley, Clayton.

Ge 11 abcd. Introduction to Earth and Planetary Sciences. *9 units each term.* Comprehensive, integrated overview of Earth and planets. Although designed as a sequence, any one term can be taken as a standalone course. Biologists are particularly welcome in Ge 11 b, as are physicists and astronomers in Ge/Ay 11 c.

a. Earth as a Planet. *(3-3-3); first term.* Systematic introduction to the physical and chemical processes that have shaped Earth as a planet over geological time, and the observable products of these processes—rock materials, minerals, land forms. Geophysics of Earth. Plate tectonics; earthquakes; igneous activity. Metamorphism and metamorphic rocks. Rock deformation and mountain building. Weathering, erosion, and sedimentary rocks. Evolution of land forms in response to wind, water, ice, and tectonic processes. The causes and recent history of climate change. The course includes one three-day field trip and a weekly laboratory section focused on the identification of rocks and minerals and the interpretation of topographic and geological maps. Instructor: Eiler.

b. Earth and the Biosphere. *(3-3-3); second term. Prerequisite: Ch 1 a.* Systematic introduction to the origin and evolution of life and its impact on the oceans, atmosphere, and climate of Earth. Topics covered include ancient Earth surface environments and the rise of atmospheric oxygen. Microbial and molecular evolution, photosynthesis, genes as fossils. Banded iron stones, microbial mats, stromatolites, and global glaciation. Biological fractionation of stable isotopes. Numerical calibration of the geological timescale, the Cambrian explosion, mass extinctions, and human evolution. The course usually includes one major field trip and laboratory studies of rocks, fossils, and geological processes. Instructors: Fischer, Kirschvink.

Ge/Ay 11 c. Planetary Sciences. *(3-0-6); third term. Prerequisites: Ma 1 ab, Ph 1 ab.* A broad introduction to the present state and early history of the solar system, including terrestrial planets, giant planets, moons, asteroids, comets, and rings. Earth-based observations, observations by planetary spacecraft, study of meteorites, and observations of extrasolar planets are used to constrain models of the dynamics and chemical processes. Instructor: Ingersoll.

d. Geophysics. *9 units (3-0-6); second term. Prerequisites: Ch 1, Ma 2 a, Ph 2 a.* An introduction to the geophysics of the solid earth; formation of planets; structure and composition of Earth; interactions between crust, mantle, and core; surface and internal dynamics; mantle convection; imaging of the interior; seismic tomography. Instructors: Clayton, Gurnis, Jackson.

Ge 13. Scientific Writing Tutorial in the Geological and Planetary Sciences. *3 units (1-0-2); third term.* This class provides the opportunity for students to gain experience in writing a substantial paper in the style typical of peer-reviewed journals, such as *Annual Reviews of Earth and Planetary Sciences*, *Geology*, *Science*, or *Nature*. Grading will be evaluated jointly by each student's adviser and the course instructor. *Fulfills the Institute scientific writing requirement.* Instructors: Kirschvink, staff.

Ge 40. Special Problems for Undergraduates. *Units to be arranged; any term.* This course provides a mechanism for undergraduates to undertake honors-type work in the geologic sciences. By arrangement with individual members of the staff. Graded pass/fail.

Ge 41 abc. Undergraduate Research and Bachelor's Thesis. *Units to be arranged; first, second, third terms.* Guidance in seeking research opportunities and in formulating a research plan leading to preparation of a bachelor's thesis is available from the GPS option representatives. Graded pass/fail.

Ge 100 abc. Geology Club. *1 unit; first, second, third terms.* Presentation of papers on research in geological and planetary sciences by guest speakers. Graded pass/fail. Instructor: Kirschvink.

Ge 101. Introduction to Geology and Geochemistry. *12 units (4-0-8); first term. Prerequisite: graduate standing or instructor's permission.* A broad, high-level survey of geology and geochemistry with emphasis on quantitative understanding. Historical deduction in the geological and planetary sciences. Plate tectonics as a unifying theory of geology. Igneous and metamorphic processes, structural geology and geomorphology; weathering and sedimentary processes. Nucleosynthesis and chemical history of the solar system; distribution of the elements in the earth; isotopic systems as tracers and clocks; evolution of the biosphere; global geochemical and biogeochemical cycles; geochemical constraints on deep Earth structure. One mandatory three-day field trip, selected laboratory exercises, and problem sets. Instructor: Asimow.

Ge 102. Introduction to Geophysics. *9 units (3-0-6); second term. Prerequisites: Ma 2, Ph 2, or Ge 108, or equivalents.* An introduction to the physics of the earth. The present internal structure and dynamics of the earth are considered in light of constraints from the gravitational and magnetic fields, seismology, and mineral physics. The fundamentals of wave propagation in earth materials are developed and applied to inferring Earth structure. The earthquake source is described in terms of seismic and geodetic signals. The following are also considered: the contributions that heat-flow, gravity, paleomagnetic, and earthquake mechanism data have made to our understanding of plate tectonics, the driving mechanism of plate tectonics, and the energy sources of mantle convection and the geodynamo. Instructor: Simons.

Ge 103. Introduction to the Solar System. *9 units (3-0-6); third term. Prerequisite: instructor's permission.* Formation and evolution of the solar system. Interiors, surfaces, and atmospheres. Orbital dynamics, chaos, and tidal friction. Cratering. Comets and asteroids. Extrasolar planetary systems. Instructor: Ingersoll.

Ge 104. Introduction to Geobiology. *9 units (3-0-6); first term. Prerequisite: instructor's permission.* Lectures about the interaction and coevolution of life and Earth surface environments. We will cover essential concepts and major outstanding questions in the field of geobiology, and introduce common approaches to solving these problems. Topics will include biological fractionation of stable isotopes; history and operation of the carbon and sulfur cycles; evolution of oxygenic photosynthesis; biomineralization; mass extinctions; analyzing biodiversity data; constructing simple mathematical models constrained by isotope mass balance; working with public databases of genetic information; phlyogenetic techniques; microbial and molecular evolution. Instructor: Fischer.

Ge 106. Introduction to Structural Geology. *9 units (3-0-6); second term. Prerequisite: Ge 11 ab.* Description and origin of main classes of deformational structures. Introduction to continuum mechanics and its application to rock deformation. Interpretation of the record of deformation of the earth's crust and upper mantle on microscopic, mesoscopic, and megascopic scales. Introduction to the tectonics of mountain belts. Instructor: Avouac.

Ge 108. Applications of Physics to the Earth Sciences. *9 units (3-0-6); first term. Prerequisites: Ph 2 and Ma 2 or equivalent.* An intermediate course in the application of the basic principles of classical physics to the earth sciences. Topics will be selected from: mechanics of rotating bodies, the two-body problem, tidal theory, oscillations and normal modes, diffusion and heat transfer, wave propagation, electro- and magneto-statics, Maxwell's equations, and elements of statistical and fluid mechanics. Instructor: Aharonson.

Ge 109. Oral Presentation. *3 units (1-0-2); third term.* Practice in the effective organization and delivery of reports before groups. Successful completion of this course is required of all candidates for degrees in the division. Graded pass/fail. Instructors: Bikle, staff.

Ge 110. Geographic Information System for Geology and Planetary Sciences. *3 units (0-3-0); first term.* Formal introduction to modern computer-based geospatial analysis. Covers methods and applications of Geographic Information Systems (GIS) in Earth and planetary sciences in the form of practical lab exercises using the ArcGIS software package and a variety of geo-referenced data (Digital Elevation Models, geodetic measurements, satellite images, geological maps). Instructor: Avouac.

Ge 111 ab. Applied Geophysics Seminar and Field Course. An introduction to the theory and application of basic geophysical field techniques consisting of a comprehensive survey of a particular field area using a variety of methods (e.g., gravity, magnetic, electrical, GPS, seismic studies, and satellite remote sensing). The course will consist of a seminar that will discuss the scientific background for the chosen field area, along with the theoretical basis and implementation of the various measurement techniques. The 4–5-day field component will be held in spring break, and the data analysis component is covered in Ge 111 b. May be repeated for credit with an instructor's permission. Instructors: Clayton, Simons.

a. Applied Geophysics Seminar. *6 units (3-3-0); second term. Prerequisite: instructor's permission.*

b. Applied Geophysics Field Course. *9 units (0-3-6); spring break, third term. Prerequisite: Ge 111 a.*

Ge 112. Sedimentology and Stratigraphy. *12 units (3-5-4); first term. Prerequisite: Ge 11 ab.* Systematic analysis of transport and deposition in sedimentary environments and the resulting composition, texture, and structure of both clastic and chemical sedimentary rocks. The nature and genesis of sequence architecture of sedimentary basins and cyclic aspects of sedimentary accumulation will be introduced. Covers the formal and practical principles of definition of stratigraphic units, correlation, and the construction of a geologic timescale. Field trip and laboratory exercises. Instructor: Grotzinger.

Ge 114 ab. Mineralogy.

a. *9 units (3-4-2); first term.* Atomic structure, composition, physical properties, occurrence, and identifying characteristics of the major mineral groups. The laboratory work involves the characterization and identification of important minerals by their physical and optical properties. Instructor: Rossman.

b. *3 units (0-2-1); first term. Prerequisite: concurrent enrollment in Ge 114 a or instructor's permission.* Additional laboratory studies of optical crystallography and the use of the petrographic microscope. Instructor: Rossman.

Ge 115 abc. Petrology and Petrography. Study of the origin and evolution of igneous and metamorphic rocks with emphasis on use of phase equilibria, microscopic petrography, and geochemistry.

a. Igneous Petrology. *6 units (3-0-3); second term. Prerequisite: Ge 114 ab.* The origin, occurrence, and classification of igneous rocks, considered mainly in the light of phase equilibria and geochemistry. Instructor: Stolper.

b. Metamorphic Petrology. *6 units (3-0-3); third term. Prerequisite: Ge 115 a.* The mineralogic and chemical composition, occurrence, and classification of metamorphic rocks; interpretation of mineral assemblages in the light of chemical equilibrium and experimental studies. Discussion centers on the use of metamorphic assemblages to understand tectonic, petrologic, and geochemical problems associated with convergent plate boundaries and intrusion of magmas into the continental crust. Instructor: Eiler.

c. Petrography Laboratory. *6 units (0-4-2); third term. Prerequisites: Ge 115 a and concurrent enrollment in Ge 115 b.* Laboratory exercises dealing with examination of igneous and metamorphic rocks in hand-sample and with the petrographic microscope. Instructor: Staff.

Ge 116. Analytical Techniques Laboratory. *6 units (1-4-1); second term.* Methods of quantitative laboratory analysis of rocks, minerals, and fluids in geological and planetary sciences. Consists of five intensive two-week modules covering scanning electron microscopy (imaging, energy-dispersive X-ray spectroscopy, electron backscatter diffraction); the electron microprobe (wavelength-dispersive X-ray spectroscopy); X-ray diffraction; optical, infrared, and Raman spectroscopy; and plasma source mass spectrometry for elemental and radiogenic isotope analysis. *Satisfies the Institute core requirement for an additional introductory laboratory course.* Instructors: Asimow, Jackson, Rossman, Farley.

Ge 120 ab. Field Geology. A comprehensive introduction to methods of geological field mapping through laboratory exercises followed by summer field camp. Instructor: Saleeby.

a. Introduction to Field Geology. *6 units (1-5-0); third term. Prerequisite: Ge 11 ab, Ge 106 (may be taken concurrently with Ge 106).* Laboratory exercises introduce geometrical and graphical techniques in the analysis of geologic maps. Field trips introduce methods of geological mapping. Given in alternate years; not offered 2010–11.

b. Summer field camp. *18 units (0-18-0); summer. Prerequisite: Ge 120 a or instructor's permission.* Intensive three-week field course in a well-exposed area of the southwestern United States covering techniques of geologic field observation, documentation, and analysis. Field work begins immediately following Commencement Day in June. Given in alternate years; not offered summer 2011.

Ge 121 abc. Advanced Field and Structural Geology. *12 units (0-9-3); first, second, third terms. Prerequisite: Ge 120 or equivalent, or instructor's permission.* Field mapping and supporting laboratory studies in topical problems related to the geology of the southwestern United States. Course provides a breadth of experience in igneous, metamorphic, and sedimentary rocks. Multiple terms of 121 may be taken more than once for credit if taught by different instructors. Instructors: Wernicke (a), Kirschvink (b), Saleeby (c).

Ge 124 ab. Paleomagnetism and Magnetostratigraphy. Application of paleomagnetism to the solution of problems in stratigraphic correlation and to the construction of a high-precision geological timescale. Instructor: Kirschvink. Given in alternate years; offered 2010–11.

a. *6 units (0-0-6); third term.* A field trip to the southwest United States or Mexico to study the physical stratigraphy and magnetic zonation, followed by lab analysis.

b. *9 units (3-3-3); third term. Prerequisite: Ge 11 ab.* The principles of rock magnetism and physical stratigraphy; emphasis on the detailed application of paleomagnetic techniques to the determination of the history of the geomagnetic field.

Ge 125. Geomorphology. *12 units (3-5-4); first term. Prerequisite: Ge 11 a or instructor's permission.* A quantitative examination of landforms, runoff generation, river hydraulics, sediment transport, erosion and deposition, hillslope creep, landslides and debris flows, glacial processes, and submarine and Martian landscapes. Field and laboratory exercises are designed to facilitate quantitative measurements and analyses of geomorphic processes. Instructor: Lamb.

Ge 126. Topics in Earth Surface Processes. *6 units (2-0-4); second term.* A seminar-style course focusing on a specific theme within geomorphology and sedimentology depending on student interest. Potential themes could include river response to climate change, bedrock erosion in tectonically active mountain belts, or delta evolution on Earth and Mars. The course will consist of student-led discussions centered on readings from peer-reviewed literature. Instructor: Lamb. Given in alternate years; not offered 2010–11.

Ge/Ch 127. Nuclear Chemistry. *9 units (3-0-6); second term. Prerequisite: instructor's permission.* A survey course in the properties of nuclei, and in atomic phenomena associated with nuclear-particle detection. Topics include rates of production and decay of radioactive nuclei; interaction of radiation with matter; nuclear masses, shapes, spins, and moments; modes of radioactive decay; nuclear fission and energy generation. Instructor: Burnett. Given in alternate years; not offered 2010–11.

Ge/Ch 128. Cosmochemistry. *9 units (3-0-6); third term. Prerequisite: instructor's permission.* Examination of the chemistry of the interstellar medium, of protostellar nebulae, and of primitive solar-system objects with a view toward establishing the relationship of the chemical evolution of atoms in the interstellar radiation field to complex molecules and aggregates in the early solar system. Emphasis will be placed on identifying the physical conditions in various objects, timescales for physical and chemical change, chemical processes leading to change, observational constraints, and various models that attempt to describe the chemical state and history of cosmological objects in general and the early solar system in particular. Not offered 2010–11.

Ge 131. Planetary Structure and Evolution. *9 units (3-0-6); third term. Prerequisite: instructor's permission.* A critical assessment of the physical and chemical processes that influence the initial condition, evolution, and current state of planets, including our planet and planetary satellites. Topics to be covered include a short survey of condensed-matter physics as it applies to planetary interiors, remote sensing of planetary interiors, planetary modeling, core formation, physics of ongoing differentiation, the role of mantle convection in thermal evolution, and generation of planetary magnetic fields. Instructor: Stevenson.

Ge/Ay 132. Atomic and Molecular Processes in Astronomy and Planetary Sciences. *9 units (3-0-6); second term. Prerequisite: instructor's permission.* Fundamental aspects of atomic and molecular spectra that enable one to infer physical conditions in astronomical, planetary, and terrestrial environments. Topics will include the structure and spectra of atoms, molecules, and solids; transition probabilities; photoionization and recombination; collisional processes; gas-phase chemical reactions; and isotopic fractionation. Each topic will be illustrated with applications in astronomy and planetary sciences, ranging from planetary atmospheres and dense interstellar clouds to the early universe. Instructor: Blake. Given in alternate years; not offered 2010–11.

Ge/Ay 133. The Formation and Evolution of Planetary Systems. *9 units (3-0-6); first term.* Review current theoretical ideas and observations pertaining to the formation and evolution of planetary systems. Topics to be covered include low-mass star formation, the protoplanetary disk, accretion and condensation in the solar nebula, the formation of gas giants, meteorites, the outer solar system, giant impacts, extrasolar planetary systems. Instructor: Blake.

Ge 135. Ophiolite Emplacement and Forearc Structure of Central California. *5 units (1-4-0). Prerequisite: instructor's permission.* Intensive preparation and follow-up lecture/laboratory sessions focusing on field observations of western Sierra Nevada ophiolite belt and Great Valley forearc basin structure. Instructor: Saleeby. Given in alternate years; not offered 2010–11.

Ge 136 abc. Regional Field Geology of the Southwestern United States. *3 units (1-0-2); first, second, or third terms, by announcement. Prerequisite: Ge 11 ab or Ge 101, or instructor's permission.* Includes approximately three days of weekend field trips into areas displaying highly varied geology. Each student is assigned the major responsibility of being the resident expert on a pertinent subject for each trip. Graded pass/fail. Instructor: Kirschvink.

Ge/Ay 137. Planetary Physics. *9 units (3-0-6); first term. Prerequisites: Ph 106 abc, ACM 95/100 abc.* Solar-system dynamics, with emphasis on slow changes in the orbit and rotation rates of planets and satellites. Topics: tidal friction, resonant orbits and rotation rates, gravitational fields of planets and satellites, dynamics of polar wandering, continental drift, and planetary rings. Given in alternate years; not offered 2010–11.

Ge 140. Introduction to Isotope Geochemistry. *9 units (3-0-6); second term. Prerequisite: instructor's permission.* An introduction to the physics and chemistry of isotopes and a broad overview of the principles and conceptual techniques used in the stable isotope geochemistry of the lighter elements (H, C, O, N, Si, S) and the origin and evolution of radiogenic parent-daughter systems in nature. Instructors: Eiler, Farley.

Ge/ESE 143. Organic Geochemistry. *9 units (3-2-4); first term. Prerequisite: Ch 41 a or equivalent.* Main topics include the analysis, properties, sources, and cycling of natural organic materials in the environment, from their production in living organisms to burial and decomposition in sediments and preservation in the rock record. Specific topics include analytical methods for organic geochemistry, lipid structure and biochemistry, composition of organic matter, factors controlling organic preservation, organic climate and CO_2 proxies, diagenesis and catagenesis, and biomarkers for ancient life. A laboratory component (three evening labs) teaches the extraction and analysis of modern and ancient organic biomarkers by GC/MS. Class includes a mandatory one-day (weekend) field trip to observe the Monterey Fm. Instructor: Sessions. Given in alternate years; offered 2010–11.

Ge/ESE 145. Isotopic Biogeochemistry Seminar. *6 units (3-0-3); first term. Prerequisite: Ge 140 or instructor's permission.* Advanced seminar to discuss research and papers in stable isotope biogeochemistry and geobiology. Topics will vary from year to year, and may be taken multiple times for credit. Instructor: Sessions. Given in alternate years; not offered 2010–11.

Ge 147. Tectonics of Western North America. *9 units (4-0-5); first term. Prerequisite: Ge 11 ab.* Major tectonic features of western North America, including adjacent craton and Pacific Ocean basin. Active plate junctures, igneous provinces, crustal uplift, and basin subsidence. Tectonic evolution from late Precambrian to recent time, and modern analogues for paleotectonic phenomena. In some years, course will focus specifically on the Southern California region basement and its disruption by Neogene to recent tectonics, with three one-day weekend local field trips spaced throughout the term. Alternates with Ge 135. Instructor: Saleeby. Given in alternate years; not offered 2010–11.

ESE/Ge 148 abc. Global Environmental Science. *9 units (3-0-6).* For course description, see Environmental Science and Engineering.

Ge/ESE 149. Marine Geochemistry. *9 units (3-0-6); third term.* Introduction to chemical oceanography and sediment geochemistry. We will address the question "Why is the ocean salty?" by examining the processes that determine the major, minor, and trace element distributions of seawater and ocean sediments. Topics include river and estuarine chemistry, air/sea exchange, nutrient uptake by the biota, radioactive tracers, redox processes in the water column and sediments, carbonate chemistry, and ventilation. Instructor: Adkins. Given in alternate years; offered 2010–11.

Ge 150. Planetary Atmospheres. *9 units (3-0-6); second term. Prerequisites: Ch 1, Ma 2, Ph 2, or equivalents.* Origin of planetary atmospheres, escape, and chemical evolution. Tenuous atmospheres: the moon, Mercury, and outer solar system satellites. Comets. Vapor-pressure atmospheres: Triton, Io, and Mars. Spectrum of dynamical regimes on Mars, Earth, Venus, Titan, and the gas giant planets. Instructor: Ingersoll.

Ge 151. Fundamentals of Planetary Surfaces. *9 units (3-3-3); third term.* Review of surface histories and processes responsible for the formation and modification of the surfaces of the terrestrial planets and the Jovian satellites. Topics: exogenic surface processes, including impact, gravitational degradation, atmospheric modification of surfaces by wind and water, and the direct interaction of surfaces with plasmas; endogenic modification of surfaces by tectonics and volcanism; surface histories of Mercury, Venus, the moon, and Mars; the surfaces of icy bodies. Instructor: Aharonson.

ESE/Ge 152. Atmospheric Radiation. *9 units (3-0-6).* For course description, see Environmental Science and Engineering.

ESE/Ge 153. Atmosphere and Climate Dynamics. *9 units (3-0-6).* For course description, see Environmental Science and Engineering.

Ge/ESE 154. Readings in Paleoclimate. *3 units (1-0-2); second term. Prerequisite: instructor's permission.* Lectures and readings in areas of current interest in paleoceanography and paleoclimate.

Ge/ESE 155. Paleoceanography. *9 units (3-0-6); third term.* Evaluation of the data and models that make up our current understanding of past climates. Emphasis will be placed on a historical introduction to the study of the past ten thousand to a few hundred thousand years, with some consideration of longer timescales. Evidence from marine and terrestrial sediments, ice cores, corals, and speleothems will be used to address the mechanisms behind natural climate variability. Models of this variability will be evaluated in light of the data. Topics will include sea level and ice volume, surface temperature evolution, atmospheric composition, deep ocean circulation, tropical climate, ENSO variability, and terrestrial/ocean linkages. Instructor: Adkins. Given in alternate years; not offered 2010–11.

Ge 156. Topics in Planetary Surfaces. *6 units (3-0-3); third term.* Reading about and discussion of current understanding of the surface of a selected terrestrial planet, major satellite, or asteroid. Important "classic" papers will be reviewed, relative to the data that are being returned from recent and current missions. May be repeated for credit. Instructor: Aharonson.

Ge/Ay 159. Planetary Evolution and Habitability. *9 units (3-0-6); second term.* Photochemistry of planetary atmospheres, comparative planetology, atmospheric evolution. What makes Earth habitable? Remote sensing of extrasolar planets, biosignatures. Instructor: Yung. Given in alternate years; offered 2010–11.

Ae/Ge/ME 160 ab. Continuum Mechanics of Fluids and Solids. *9 units (3-0-6).* For course description, see Aerospace.

Ge 161. Plate Tectonics. *9 units (3-0-6); first term. Prerequisite: Ge 11 ab or equivalent.* Geophysical and geological observations related to plate tectonic theory. Instantaneous and finite motion of rigid plates on a sphere; marine magnetic and paleomagnetic measurements; seismicity and tectonics of plate boundaries; reference frames and absolute plate motions. Interpretations of geologic data in the context of plate tectonics; plate tectonic evolution of the ocean basins. Instructor: Stock.

Ge 162. Seismology. *9 units (3-0-6); second term. Prerequisite: ACM 95/100 abc or equivalent.* Review of concepts in classical seismology. Topics to be covered: basic theories of wave propagation in the earth, instrumentation, Earth's structure and tomography, theory of the seismic source, physics of earthquakes, and seismic risk. Emphasis will be placed on how quantitative mathematical and physical methods are used to understand complex natural processes, such as earthquakes. Instructor: Ampuero.

Ge 163. Geodynamics. *9 units (3-0-6); third term. Prerequisite: Ae/Ge/ME 160 ab.* Quantitative introduction to the dynamics of the earth, including core, mantle, lithosphere, and crust. Mechanical models are developed for each of these regions and compared to a variety of data sets. Potential theory applied to the gravitational and geomagnetic fields. Special attention is given to the dynamics of plate tectonics and the earthquake cycle. Instructor: Gurnis.

Ge 164. Mineral Physics. *9 units (3-0-6); second term. Prerequisites: Ge 11 ad or equivalent, or instructor's permission.* Introduction to the mineral physics of Earth's interior. Topics covered: mineralogy and phase transitions at high pressures and temperatures; elasticity and equations of state; vibrational, electronic, and transport properties; application of mineral physics data to Earth and planetary interiors. Instructor: Jackson. Given in alternate years; offered 2010–11.

Ge 165. Geophysical Data Analysis. *9 units (3-0-6); first term. Prerequisites: basic linear algebra and Fourier transforms.* Introduction to modern digital analysis: discrete Fourier transforms, Z-transforms, filters, deconvolution, auto-regressive models, spectral estimation, basic statistics, 1-D wavelets, model fitting via singular valued decomposition. Instructor: Clayton. Not offered 2010–11.

Ge 167. Tectonic Geodesy. *9 units (3-0-6); third term.* An introduction to the use of modern geodetic observations (e.g., GPS and InSAR) to constrain crustal deformation models. Secular velocity fields, coseismic and time-dependent processes; volcano deformation and seasonal loading phenomena. Basic inverse approaches for parameter estimation and basic temporal filtering algorithms. Instructor: Simons.

Ge 168. Crustal Geophysics. *9 units (3-0-6); second term. Prerequisite: ACM 95/100 or equivalent, or instructor's permission.* The analysis of geophysical data related to crust processes. Topics include reflection and refraction seismology, tomography, receiver functions, surface waves, and gravity. Instructor: Clayton.

Ge 169 abc. Readings in Geophysics. *6 units (3-0-3); first, second, third terms.* Reading courses are offered to teach students to read critically the work of others and to broaden their knowledge about specific topics. Each student will be required to write a short summary of each paper that summarizes the main goals of the paper, to give an assessment of how well the author achieved those goals, and to point out related issues not discussed in the paper. Each student will be expected to lead the discussion on one or more papers. The leader will summarize the discussion on the paper(s) in writing. A list of topics offered each year will be posted on the Web. Individual terms may be taken for credit multiple times without regard to sequence. Instructor: Staff.

Ge/ESE 170. Microbial Ecology. *9 units (3-2-4); third term. Prerequisite: ESE/Bi 166.* Structural, phylogenetic, and metabolic diversity of microorganisms in nature. The course explores microbial interactions, relationships between diversity and physiology in modern and ancient environments, and influence of microbial community structure on biogeochemical cycles. Introduction to ecological principles and molecular approaches used in microbial ecology and geobiological investigations. Instructor: Orphan.

ESE/Ge/Ch 171. Atmospheric Chemistry I. *9 units (3-0-6).* For course description, see Environmental Science and Engineering.

ESE/Ge/Ch 172. Atmospheric Chemistry II. *3 units (3-0-0).* For course description, see Environmental Science and Engineering.

ESE/Ge 173. Topics in Atmosphere and Ocean Dynamics. *9 units (3-0-6).* For course description, see Environmental Science and Engineering.

Ge 174. Geobiological Constraints on Earth History. *9 units (3-1-5); second term. Prerequisite: instructor's permission.* Systematic analysis of the origin and evolution of life in the solar system as read through the geological record. Effects of global glaciations, volcanism, and impact processes on the atmosphere, hydrosphere, and climate of Earth. Magnetofossils, genes as fossils, banded iron stones, algal mats, stromatolites, global glaciation, mass extinction events, the Cambrian Explosion, human and molecular evolution. The course usually includes one or two major field trips, in which each student is assigned the responsibility of being the resident expert on a pertinent subject for each trip. Instructor: Kirschvink.

ESE/Ch/Ge 175 ab. Environmental Organic Chemistry. *9 units (3-0-6).* For course description, see Environmental Science and Engineering.

Ge 177. Active Tectonics. *12 units (3-3-6); second term. Prerequisites: Ge 112 and Ge 106 or equivalent.* Introduction to techniques for identifying and quantifying active tectonic processes. Geomorphology, stratigraphy, structural geology, and geodesy applied to the study of active faults and folds in a variety of tectonic settings. Relation of seismicity and geodetic measurements to geologic structure and active tectonics processes. Review of case studies of selected earthquakes. Instructor: Avouac. Given in alternate years; not offered 2010–11.

Ge 179 abc. Seismological Laboratory Seminar. *1 unit; first, second, third terms.* Presentation of current research in geophysics by students, staff, and visitors. Graded pass/fail. Instructor: Helmberger.

Ge 190. The Nature and Evolution of the Earth. *Units to be arranged. Offered by announcement only.* Advanced-level discussions of problems of current interest in the earth sciences. Students may enroll for any or all terms of this course without regard to sequence. Instructor: Staff.

Ge 191. Special Topics in Geochemistry. *Units to be arranged. Offered by announcement only.* Advanced-level discussions of problems of current interest in geochemistry. Students may enroll for any or all terms of this course without regard to sequence. Instructor: Staff.

Ge 192. Special Topics in the Geological Sciences. *Units to be arranged. Offered by announcement only.* Advanced-level discussions of problems of current interest in the geological sciences. Students may enroll for any or all terms of this course without regard to sequence. Instructor: Staff.

Ge 193. Special Topics in Geophysics. *Units to be arranged. Offered by announcement only.* Advanced-level discussions of problems of current interest in geophysics. Students may enroll for any or all terms of this course without regard to sequence. Instructor: Staff.

Ge 194. Special Topics in the Planetary Sciences. *Units to be arranged. Offered by announcement only.* Advanced-level discussions of problems of current interest in the planetary sciences. Students may enroll for any or all terms of this course without regard to sequence. Instructor: Staff.

Ge 195. Special Opportunities in Field Geology. *Units to be arranged. Offered by announcement only.* Field experiences in different geological settings. Supporting lectures will usually occur before and during the field experience. This course will be scheduled only when special opportunities arise. Class may be taken more than once. Instructor: Staff.

Ge 196. Special Topics in Atmospheres and Oceans. *Units to be arranged. Offered by announcement only.* Advanced-level discussions of problems of current interest in atmospheric and ocean sciences. Instructor: Staff.

Ge 211. Applied Geophysics II. *Units to be arranged. Prerequisite: instructor's permission.* Intensive geophysical field experience in either marine or continental settings. Marine option will include participation in a student training cruise, with several weeks aboard a geophysical research vessel, conducting geophysical measurements (multibeam bathymetry, gravity, magnetics, and seismics), and processing and interpreting the data. Supporting lectures and problem sets on the theoretical basis of the relevant geophysical techniques and the tectonic background of the survey area will occur before and during the training cruise. The course might be offered in a similar format in other isolated situations. The course will be scheduled only when opportunities arise and this usually means that only six months' notice can be given. Auditing not permitted. Class may be taken more than once. Instructors: Stock, Clayton, Gurnis.

Ge 212. Thermodynamics of Geological Systems. *9 units (3-0-6); third term. Prerequisites: Either Ch 21 abc, Ge 115 a, or equivalents.* Chemical thermodynamics as applied to geological and geochemical problems. Classical thermodynamics, including stability criteria, homogeneous and heterogeneous equilibria, equilibria subject to generalized constraints, equations of state, ideal and non-ideal solutions, redox systems, and electrolyte conventions. Brief discussion of statistical foundations and an introduction to the thermodynamics of irreversible processes. Instructor: Asimow. Given in alternate years; offered 2010–11.

Ge 214. Spectroscopy of Minerals. *9 units (3-0-6); third term. Prerequisites: Ge 114 a, Ch 21 ab, or instructor's permission.* An overview of the interaction of minerals with electromagnetic radiation from gamma rays to microwaves. Particular emphasis is placed on visible, infrared, Raman, and Mössbauer spectroscopies as applied to mineralogical problems such as phase identification, chemical analysis, site populations, and origin of color and pleochroism. Instructor: Rossman. Given in alternate years; offered 2010–11.

Ge 215. Topics in Advanced Petrology. *12 units (4-0-8); third term. Prerequisite: Ge 115 ab or instructor's permission.* Lectures, readings, seminars, and/or laboratory studies in igneous or metamorphic petrology, paragenesis, and petrogenesis. The course may cover experimental, computational, or analytical methods. Format and content are flexible according to the needs of the students. Instructor: Asimow. Given in alternate years; not offered 2010–11.

Ge 225 abc. Planetary Sciences Seminar. *1 unit; first, second, third terms.* Required of all planetary-science graduate students; others welcome. First term: current research by staff and students. Second and third terms: planetary research with spacecraft and current developments in planetary science. Instructor: Staff.

Ge/ESE/CE 226. Sediment Transport Mechanics and Morphodynamics. *9 units (3-0-6); third term. Prerequisites: ACM 95/100 bc and ME 19 ab, or equivalents.* This course will consist of lectures and problem sets on the physics of sediment transport, erosion, and deposition. Topics will include turbulent boundary layers, open-channel hydraulics and resistance, sediment-size distributions, incipient sediment motion, bed load, suspended load, and bed forms. The content is relevant to a variety of dilute geophysical flows (e.g., turbidity currents, powder avalanches, ocean currents, wind), but an emphasis will be made on application to rivers. Instructor: Lamb. Given in alternate years; offered 2010–11.

Ge 232. Chemistry of the Solar System. *9 units (3-0-6); second term. Prerequisite: Ge 140 or instructor's permission.* Advanced course using both chemical and isotopic data to evaluate the current state of knowledge concerning the composition of major segments of the solar system, viz., solar and meteoritic abundance data to infer the average solar-system composition; chemistry of meteorites as a clue to initial conditions in the solar nebula; bulk composition of the earth and moon; constraints on the bulk composition of the other planets, emphasizing data on atmospheric constituents. Instructor: Burnett. Given in alternate years; offered 2010–11.

Ge/Bi 244. Paleobiology Seminar. *6 units (3-0-3); third term.* Critical reviews and discussion of classic investigations and current research in paleoecology, evolution, and biogeochemistry. Instructor: Kirschvink.

Ge/Bi 246. Molecular Geobiology Seminar. *6 units (2-0-4); second term. Recommended preparation: ESE/Bi 166.* Critical reviews and discussion of classic papers and current research in microbiology and geomicrobiology. As the topics will vary from year to year, it may be taken multiple times. Instructor: Orphan. Given in alternate years; offered 2010–11.

Ge 261. Advanced Seismology. *9 units (3-0-6); third term.* Continuation of Ge 162 with special emphasis on particular complex problems; includes generalizations of analytical methods to handle nonplanar structures and methods of interfacing numerical-analytical codes in two and three dimensions; construction of Earth models using tomographic methods and synthetics. Requires a class project. Instructor: Helmberger.

Ge 263. Computational Geophysics. *9 units (3-0-6); second term. Prerequisites: introductory class in geophysics, class in partial differential equations, some programming experience.* Finite-difference, pseudo-spectral, finite-element, and spectral-element methods will be presented and applied to a number of geophysical problems including heat flow, deformation, and wave propagation. Students will program simple versions of methods. Instructors: Clayton, Gurnis, Ampuero. Given in alternate years; offered 2010–11.

Ae/Ge/ME 266 ab. Dynamic Fracture and Frictional Faulting. *9 units (3-0-6).* For course description, see Aerospace.

Ge 268. Mantle Dynamics. *9 units (3-0-6); first term. Prerequisites: Ge 163 and Ge 263.* Analysis of mantle dynamics and connection with surface processes, especially plate tectonics. Selected problems will be examined, including the mechanics of subduction, mantle plumes, mantle convection, convective mixing, thermal evolution, and interpretation of seismic tomography. Term project using numerical models required. Instructor: Gurnis. Given in alternate years; not offered 2010–11.

Ge 270. Continental Tectonics. *9 units (3-0-6); first term. Prerequisites: ACM 95/100 or ACM 113; Ge 11 ab, Ge 106, Ge 162, or Ge 161.* The nature of nonplate, finite deformation processes in the evolution of the continental lithosphere, using the Alpine orogen as an example. Rheological stratification; isostatic and flexural response to near-vertical loads; rifting and associated basin development; collision and strike-slip tectonics; deep crustal processes. Instructor: Wernicke. Given in alternate years; not offered 2010–11.

Ge 277. Active Tectonics Seminar. *6 units (2-0-4); second term.* Discussion of key issues in active tectonics based on a review of the literature. The topic of the seminar is adjusted every year based on students' interest and recent literature. Instructor: Avouac.

Ge 282 abc. Division Seminar. *1 unit; first, second, third terms.* Presentation of papers by invited investigators. Graded pass/fail.

Ge 297. Advanced Study. *Units to be arranged.*

Ge 299. Thesis Research. Original investigation, designed to give training in methods of research, to serve as theses for higher degrees, and to yield contributions to scientific knowledge.

HISTORY

Hum/H 1 ab. East Asian History. *9 units (3-0-6).* For course description, see Humanities.

Hum/H 2. American History. *9 units (3-0-6).* For course description, see Humanities.

Hum/H 3 abc. European Civilization. *9 units (3-0-6).* For course description, see Humanities.

Hum/H 4 abc. Civilization, Science, and Archaeology. *9 units (3-0-6).* For course description, see Humanities.

Hum/H/HPS 10. Introduction to the History of Science. *9 units (3-0-6).* For course description, see Humanities.

Hum/H/HPS 11. History of Astronomy and Cosmology. *9 units (3-0-6).* For course description, see Humanities.

H 40. Reading in History. *Units to be determined for the individual by the division. Elective, in any term.* Reading in history and related subjects, done either in connection with the regular courses or independently, but under the direction of members of the department. A brief written report will usually be required. Graded pass/fail. *Not available for credit toward humanities–social science requirement.*

H 98. Reading in History. *9 units (1-0-8). Prerequisite: instructor's permission.* An individual program of directed reading in history, in areas not covered by regular courses. Instructor: Staff.

H 99 abc. Research Tutorial. *9 units (1-0-8). Prerequisite: instructor's permission.* Students will work with the instructor in the preparation of a research paper, which will form the basis of an oral examination. Instructor: Staff.

H 108 a. The Early Middle Ages. *9 units (3-0-6); first term.* This course is designed to introduce students to the formative period of Western medieval history, roughly from the fourth through the tenth centuries. It will emphasize the development of a new civilization from the fusion of Roman, Germanic, and Christian traditions, with a focus on the Frankish world. The course focuses on the reading, analysis, and discussion of primary sources. Instructor: Brown.

H 108 b. The High Middle Ages. *9 units (3-0-6); second term.* This course is designed to introduce students to European history between 1000 and 1400. It will provide a topical as well as chronological examination of the economic, social, political, and religious evolution of western Europe during this period, with a focus on France, Italy, England, and Germany. The course emphasizes the reading, analysis, and discussion of primary sources. Instructor: Brown.

H 109. Medieval Knighthood. *9 units (3-0-6); second term.* This course tells the story of the knight from his beginnings in the early Middle Ages, through his zenith in the 11th, 12th, and 13th centuries, to his decline and transformation in the late medieval and early modern periods. The course treats the knight not simply as a military phenomenon but also as a social, political, religious, and cultural figure who personified many of the elements that set the Middle Ages apart. Not offered 2010–11.

H 110. Saints, Sinners, and Sexuality in the Medieval World. *9 units (3-0-6); third term.* This course will investigate medieval conceptions of sanctity, transgression, and appropriate behavior for men and women. We will examine institutions as well as individuals, and explore real situations as well as the imaginary realms created in romances and manuscript marginalia. From the earliest Christian martyrs to Joan of Arc, we will investigate a wide range of sources—literary, artistic, and documentary—to get at the often contradictory but always fascinating intersections of faith, gender, and the forbidden in the medieval world. Not offered 2010–11.

H 111. The Medieval Church. *9 units (3-0-6); offered by announcement.* This course takes students through the history of the medieval Christian Church in Europe, from its roots in Roman Palestine, through the zenith of its power in the high Middle Ages, to its decline on the eve of the Reformation. The course focuses on the church less as a religion (although it will by necessity deal with some basic theology) than as an institution that came to have an enormous political, social, cultural, and economic impact on medieval life, and for a brief time made Rome once more the mistress of Europe. Not offered 2010–11.

H 112. The Vikings. *9 units (3-0-6); third term.* This course will take on the Scandinavian seafaring warriors of the 8th–11th centuries as a historical problem. What were the Vikings, where did they come from, and how they did they differ from the Scandinavian and north German pirates and raiders who preceded them? Were they really the horned-helmeted, bloodthirsty barbarians depicted by modern popular media and by many medieval chronicles? What effect did they have in their roughly two centuries of raiding and colonization on the civilizations of medieval and ultimately modern Europe? Not offered 2010–11.

H 115 abc. British History. *9 units (3-0-6); first, second, third terms.* The political and cultural development of Great Britain from the early modern period to the twentieth century. H 115 a covers the Reformation and the making of a Protestant state (1500–1700). H 115 b examines the Enlightenment and British responses to revolutions in France and America (1700–1830). H 115 c is devoted to the Victorian and Edwardian eras (1830–1918). H 115 a is not a prerequisite for H 115 b; neither it nor H 115 b is a prerequisite for H 115 c. Not offered 2010–11.

H 116. Studies in Narrative: History, Fiction, and Storytelling. *9 units (3-0-6); second term.* This course examines the fraught relationship between historical and literary narratives, two interdependent but often opposed forms of storytelling. It will look at works that raise the issue of veracity and storytelling, including fictions like Graham Swift's *Waterland*, films such as Kurosawa's *Rashomon*, and the "historical novellas" in Simon Schama's book *Dead Certainties*. It will also investigate in some detail the works of American, French, and Italian historians who have tried to solve this problem by turning to so-called microhistory. Not offered 2010–11.

H 118. Histories of Collecting. *9 units (3-0-6); second term.* This course examines the history and theory of collecting, concentrating on collectors, collections, and collecting in the West since the Renaissance. It will include field trips to collections around Los Angeles, including the Huntington Art Gallery and the Museum of Jurassic Technology, and the examination of issues such as forgery and the workings of art markets. Instructor: Spieth.

H/Art 119. Art Worlds. *9 units (3-0-6); third term.* Among theorists and practitioners of art, the "art world" has come to be seen as a central force in the production of contemporary art. But what is the art world? When and how did it come to assume this remarkable importance? Drawing on resources including social history, philosophical aesthetics, artists' writings and anthropological theory, this course will examine crucial moments in the formation and changing conception of the art world. Topics include the relation of art worlds to the valuation, collecting, and market for art; the ambivalent relations of the art world to artistic avant-gardes; and the comparative strength of the art world's position in the age of 21st-century globalization. Objects from local collections, and local collections themselves, will be central to the analysis. The course will include a number of field trips as well as presentations by contemporary artists. Instructors: Brewer, M. Hunter.

H 121. American Radicalism. *9 units (3-0-6); offered by announcement.* The course will cover a number of radical social, political, and artistic movements in 20th-century America. A focus on the first two decades of the century will center around the poet, journalist, and revolutionary John Reed and his circle in Greenwich Village. Topics will include their involvement with artistic experimentation, the Industrial Workers of the World, the Mexican Revolution, the Russian Revolution, and the movements for birth control and against American involvement in World War I. Other areas of concentration will be the Great Depression of the '30s, with its leftist political and labor actions, and the freewheeling radicalism of the '60s, including the anti-Vietnam protests, Students for a Democratic Society, and the ethnic struggles for social and political equality. Some reference will be made to the antiglobalization movements of today. Not offered 2010–11.

H 122. Household and Family Forms over Time. *9 units (3-0-6); first term.* This course examines the wide variety of family forms and household structures in past societies, as well as the social, cultural, institutional, and economic variables that influenced them. The course focuses mainly on Europe from about 1600 to the present, as this is the area for which most research has been done, but there will be some discussion of other parts of the world, including Asia, Africa, and North and South America. Special attention is given to comparisons among different societies. Instructor: Dennison.

H/SS 124. Problems in Historical Demography. *9 units (3-0-6).* Birth, marriage, and death—the most basic events in people's lives—are inextricably linked to larger economic and social phenomena. An understanding of these basic events can thus shed light on the economic and social world inhabited by people in the past. In this course students will be introduced to the sources and methods used by historical demographers to construct demographic measures for past populations. In addition, the course will cover a broad range of problems in historical demography, including mortality crises, fertility control, infant mortality, and the role of economic and social institutions in demographic change. While the emphasis is on societies in the past, there will be some discussion of modern demographic trends in various parts of the world. Not offered 2010–11.

H 130. Postmodern History. *9 units (3-0-6); offered by announcement.* In recent years some historians have experimented with new and innovative ways of telling the past—on the printed page, using film and video, and on the Internet. The course will focus on these new approaches to historical presentation and knowledge. Students will read, watch, and interact with various examples of these innovative historical works. They will also be exposed to the critiques of traditional historical writing from philosophers, literary critics, and postmodern theorists, which provide intellectual underpinning for experimenting with new forms of history. Not offered 2010–11.

H/F 131. History on Film. *9 units (2-2-5); third term.* An investigation into the variety of ways history has been and can be represented on the screen. Some terms the focus will be a specific historical period or nation; other terms the focus will be the nature of film as a medium for history and biography. The class will include weekly screenings of films as well as weekly discussion sections. Not offered 2010–11.

H/F 133. Topics in Film History. *9 units (2-2-5); offered by announcement.* The course will focus each term on one kind of motion picture—either a film genre, or films made by an individual director, or from a single nation or region of the world or particular historical era. Included are weekly screenings, readings on film, a weekly discussion meeting, and a term paper. Instructor: Rosenstone.

H/F 134. The Science Fiction Film. *9 units (2-2-5); third term.* This course will introduce students to some of the classic works of the science fiction film from the earliest days of cinema until the present. It will analyze aesthetic, historical, and social documents, and will show that such films, while describing alternative, hypothetical, and futurist worlds, also serve as a commentary upon and/or a critique of contemporary (to the film) historical, social, political, and ideological systems and attitudes. Instructor: Rosenstone.

H 135. War, Conquest, and Empires. *9 units (3-0-6); offered by announcement.* This course will use historical examples of war and conquest and ask why some periods of history were times of warfare and why certain countries developed a comparative advantage in violence. The examples will come from the history of Europe and Asia, from ancient times up until World War I, and the emphasis throughout will be on the interplay between politics, military technology, and social conditions. Not offered 2010–11.

H/F 136. Ethnic Visions. *9 units (2-2-5); offered by announcement.* In recent decades, directors from ethnic minorities that are often un- or misrepresented in mainstream Hollywood films have been making dramatic features depicting the history, problems, and prospects of their own communities. This course will feature a selection of such films by directors from African, Latino, Asian, Muslim, and European American ethnic groups, with an eye toward assessing the similarities and differences in the processes of immigration, acculturation, and Americanization. Not offered 2010–11.

H/L 142. Perspectives on History through Russian Literature. *9 units (3-0-6), second term.* The Russian intelligentsia registered the arrival of modern urban society with a highly articulate sensitivity, perhaps because these changes—industrialization, the breakdown of traditional hierarchies and social bonds, the questioning of traditional beliefs—came to Russia so suddenly. This gives their writings a paradigmatic quality; the modern dilemmas that still haunt us are made so eloquently explicit in them that they have served as models for succeeding generations of writers and social critics. This course explores these writings (in English translation) against the background of Russian society, focusing especially on particular works of Chekhov, Dostoevsky, Goncharov, Tolstoy, and Turgenev. Instructor: Dennison.

H 143. Race Matters: Transatlantic Perspectives (1500–1800). *9 units (3-0-6), second term.* This course examines the various configurations of race that developed within the Atlantic world in the early modern period. The "discovery" of the New World and the intensification of trade between Europe, Africa, and America opened up, first in Europe and later throughout the Atlantic space, a crucial debate about humankind, its nature, classification, and history. The conceptualization of race is a key issue in this context. Three analytical perspectives will be examined in turn. The first concerns the shift from the Medieval lineage categorization to the broad "physical" and "moral" classifications. The second is related to the entangled relations of gender and race, indebted to the Enlightenment's reflections on civilization. The third perspective is rooted in the multiplication of discourses about race and history at the end of the eighteenth century, when the authority of European philosophers diminished in the face of emerging American voices. Instructor: Napolitano.

H 144. Enlightenment's Historiographies in the Making: New Objects, Methods, and Debates. *9 units (3-0-6), third term.* Criticized as chiefly responsible for the disenchantment of the world, for the "orientalization" of otherness, for the forging of race, or the shaping of biopolitics, the Enlightenment is continuously put under examination by postmodern theories. Its plural and competitive historiographies deserve more attention in order to rethink the major concepts of Enlightenment(s). The course will examine, among other topics, the new idea of progress, civilization, universalism, as well as the first histories fully devoted to women, understood as the first attempts to discuss a masculine and white vision of the world. It will be based on in-depth analysis of primary source materials, including historical accounts, philosophical treatises, geographies, natural descriptions, political essays, and travelogues. This material will be studied in a comparative context with reference to the decisive events of the period. Not offered 2010–11.

Law/PS/H 148 ab. The Supreme Court in U.S. History. *9 units (3-0-6)*. For course description, see Law.

Art/H 155. Making and Knowing in Early Modern Europe. *9 units (3-0-6)*. For course description, see Art History.

HPS/H 156. The History of Modern Science. *9 units (3-0-6)*. For course description, see History and Philosophy of Science.

HPS/H 158. The Scientific Revolution. *9 units (3-0-6)*. For course description, see History and Philosophy of Science.

HPS/H 159. The Cold War and American Science. *9 units (3-0-6)*. For course description, see History and Philosophy of Science.

HPS/H 160 ab. Einstein and His Generation: The History of Modern Physical Sciences. *9 units (3-0-6)*. For course description, see History and Philosophy of Science.

H 161. Selected Topics in History. *9 units (3-0-6)*; offered by announcement. Instructors: Staff, visiting lecturers.

HPS/H 162. Social Studies of Science. *9 units (3-0-6)*. For course description, see History and Philosophy of Science.

HPS/H 166. Historical Perspectives on the Relations between Science and Religion. *9 units (3-0-6)*. For course description, see History and Philosophy of Science.

HPS/H 167. Experimenting with History/Historic Experiment. *9 units (3-0-6)*. For course description, see History and Philosophy of Science.

HPS/H 168. History of Electromagnetism and Heat Science. *9 units (3-0-6)*. For course description, see History and Philosophy of Science.

HPS/H 169. Selected Topics in the History of Science and Technology. *9 units (3-0-6)*. For course description, see History and Philosophy of Science.

HPS/H 170. History of Light from Antiquity to the 20th Century. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/H 171. History of Mechanics from Galileo through Euler. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/H 172. History of Mathematics: A Global View with Close-ups. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/H/Pl 173. History of Chemistry. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/H 174. Early Greek Astronomy. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/H 175. Matter, Motion, and Force: Physical Astronomy from Ptolemy to Newton. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/H 178. Galileo's Astronomy and Conflicts with the Church. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/H 179. Cambridge Scientific Minds: How We See Them; How They See Themselves. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/H 180. Physics and Philosophy from the Scientific Revolution to the 20th Century. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/H 181. Evidence, Measurement, and the Uses of Data in the Early Modern Period. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/H 182. Show and Tell: 3-D Models for the Visualization of Complex Concepts in the 16th and 17th centuries. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

Art/H 183. Spectacle: From the Court Masque to the Great Exhibition of 1851. *9 units (3-0-6).* For course description, see Art History.

H/HPS 184. Medicine and Disease from Antiquity to the Nineteenth Century. *9 units (3-0-6); second term.* This course takes as its subject the intellectual, social, and institutional developments in medicine from the time of Hippocrates to modern disease theory. The specific historical periods covered will vary depending on the decision of the instructor, but topics may include early and late Greek medicine; medicine in the Mediterranean; healing and disease in the Middle Ages; the role of religion in medicine; medical professionalization; anatomy and surgery; botany, apothecaries, and merchants; illness and healing in the New World; medicine in the scientific revolution; modern Western medicine and the emergence of alternative medicine. Instructor: Archambeau.

H/HPS 185. Angels and Monsters. *9 units (3-0-6); third term.* We read Cervantes's masterpiece, *Don Quixote*, with a view to some of the great upheavals that shaped the early modern world—from Europe's discovery of the Americas, to the demise of the feudal system and proliferation of indigent masses, to the rise of the Reformation and Counter-Reformation, to the wars against heretics and infidels, and to the disastrous decline of the Hapsburg dynasty. Students are asked to consider the dynamics between truth and falsehood, history and fiction, that intervene in Cervantes's novelization of the moral and material dilemmas of his time. Instructor: Gomez.

HPS/H 186. The Sciences in the Romantic Era. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

H 201. Reading and Research for Graduate Students. *Units to be determined for the individual by the division.*

HISTORY AND PHILOSOPHY OF SCIENCE

Hum/H/HPS 10. Introduction to the History of Science. *9 units (3-0-6).* For course description, see Humanities.

Hum/H/HPS 11. History of Astronomy and Cosmology. *9 units (3-0-6).* For course description, see Humanities.

HPS 98. Reading in History and Philosophy of Science. *9 units (1-0-8). Prerequisite: instructor's permission.* An individual program of directed reading in history and philosophy of science, in areas not covered by regular courses. Instructor: Staff.

HPS 102 ab. Senior Research Seminar. *12 units (2-0-10). Offered in any two consecutive terms, by arrangement with HPS faculty.* Under the guidance of an HPS faculty member, students will research and write a focused research paper of 15,000 words (approximately 50 pages). Work in the first term will comprise intensive reading in the relevant literature and/or archival or other primary source research. In the second term, students will draft and revise their paper. Open to seniors in the HPS option and to others by special permission of an HPS faculty member. Instructor: Staff.

HPS 103. Public Lecture Series. *1 unit; first, second, third terms.* Student attend four lectures, featuring speakers from outside Caltech, on topics in the history and philosophy of science. Students may choose from a variety of regularly scheduled HPS lectures, including HPS seminars, Harris lectures, and Munroe seminars (history or philosophy of science only). Graded on attendance. *Not available for credit toward the humanities–social science requirement.* Graded pass/fail. Instructors: Visiting lecturers.

HPS 104. Forbidden Knowledge. *9 units (3-0-6).* When and how has the notion of freedom of knowledge and teaching in science emerged? What kinds of restrictions have been placed on scientists, their publications and institutions? Who restrained scientific knowledge of what sorts; for what reasons; and how successfully? These questions will be addressed by looking at some canonical cases in the history of science, such as Copernicus and Galileo. But we will also move into more recent history, discussing work on the atomic bomb, genetic engineering, and global warming. Not offered 2010–11.

HPS 105. Science and Literature. *9 units (3-0-6).* This course explores the relationships between the sciences and the humanities, from the point of view of literary-scientific interactions. Issues to be addressed include the "Two Cultures" debate over the years: Huxley vs. Arnold in the late 19th century; Snow vs. Leavis in the mid 20th century; the Science Wars of the late 20th century. Problems of representing scientific content in literary works and the consequences of examining scientific writing from a literary perspective will also be addressed. Readings will be drawn from a variety of genres, including novels, short stories, poetry, essays, and scientific texts. Not offered 2010–11.

HPS/Pl 120. Introduction to Philosophy of Science. *9 units (3-0-6); third term.* An introduction to fundamental philosophical problems concerning the nature of science. Topics may include the character of scientific explanation, criteria for the conformation and falsification of scientific theories, the relationship between theory and observation, philosophical accounts of the concept of "law of nature," causation, chance, realism about unobservable entities, the objectivity of science, and issues having to do with the ways in which scientific knowledge changes over time. Instructor: Hitchcock.

HPS/Pl 121. Causation and Explanation. *9 units (3-0-6); first term.* An examination of theories of causation and explanation in philosophy and neighboring disciplines. Topics discussed may include probabilistic and counterfactual treatments of causation, the role of statistical evidence and experimentation in causal inference, and the deductive-nomological model of explanation. The treatment of these topics by important figures from the history of philosophy such as Aristotle, Descartes, and Hume may also be considered. Not offered 2010–11.

HPS/Pl 122. Confirmation and Induction. *9 units (3-0-6); offered by announcement.* Philosophical and conceptual issues arising from theories of confirmation and induction. Topics include Hume's "old" problem of induction; Goodman's "new" riddle of induction and various notions of "projectability"; inductive logic; Bayesian confirmation theory; and other theories of confirmation. Not offered 2010–11.

HPS/Pl 124. Philosophy of Space and Time. *9 units (3-0-6); offered by announcement.* This course will focus on questions about the nature of space and time, particularly as they arise in connection with physical theory. Topics may include the nature and existence of space, time, and motion; the relationship between geometry and physical space (or space-time); entropy and the direction of time; the nature of simultaneity; and the possibility of time travel. Not offered 2010–11.

HPS/Pl 125. Philosophical Issues in Quantum Physics. *9 units (3-0-6); second term.* This course will focus on conceptual issues that arise within quantum physics. Topics may include determinism and indeterminism; Einstein's critiques of quantum theory; the interpretation of quantum measurement; and quantum logic. Not offered 2010–11.

HPS/Pl 128. Philosophy of Mathematics. *9 units (3-0-6); third term.* An examination of conceptual issues that arise in mathematics. The sorts of issues addressed may include the following: Are mathematical objects such as numbers in some sense real? How do we obtain knowledge of the mathematical world? Are proofs the only legitimate source of mathematical knowledge? What is the relationship between mathematics and the world? How is it possible to apply abstract theory to the world? Views of major historical figures such as Plato, Hume, Kant, and Mill, as well as of contemporary writers are examined. The course will also examine philosophical issues that arise in particular areas of mathematics such as probability theory and geometry. Instructor: Hitchcock.

HPS/Pl 129. Introduction to Philosophy of Biology. *9 units (3-0-6).* Philosophical and conceptual issues relating to the biological sciences. Topics covered may include the logical structure of evolutionary theory, units of selection, optimization theory, the nature of species, reductionism, teleological and functional reasoning, and ethical issues arising from contemporary biological research. Not offered 2010–11.

HPS/Pl 130. Philosophy and Biology. *9 units (3-0-6); first, second terms.* This course will examine the impact of recent advances in biological sciences for studies of the mind, behavior, and society. Topics may include evolutionary psychology, the relation between evolution and development, the impact of molecular genetics on the theory of evolution, mathematical modeling of evolution and artificial evolution, philosophical and social issues raised by modern molecular biology. Not offered 2010–11.

HPS/Pl 132. Introduction to Philosophy of Mind and Psychology. *9 units (3-0-6); offered by announcement.* An introduction to the mind-body problem. The course attempts, from the time of Descartes to the present, to understand the nature of the mind and its relation to the body and brain. Topics to be addressed may include dualism, behaviorism, functionalism, computationalism, neurophilosophy, consciousness and qualia, scientific psychology vs. "folk" psychology, the nature of emotion, knowledge of other minds. Not offered 2010–11.

HPS/Pl 133. Philosophy and Neuroscience. *9 units (3-0-6); third term.* This course will examine the impact of recent advances in neuroscience on traditional philosophical problems. Topics may include the nature of free will in light of work on the neural basis of decision making; the nature of consciousness, knowledge, or learning; the mind/brain from the perspective of neural computation; and the neural foundations of cognitive science. Instructor: Quartz.

HPS/Pl 134. Current Issues in Philosophical Psychology. *9 units (3-0-6); second, third terms.* An in-depth examination of one or more issues at the intersection of contemporary philosophy and the brain and behavioral sciences. Topics may include the development of a theory of mind and self-representation, theories of representation and neural coding, the nature of rationality, the nature and causes of psychopathology, learning and innateness, the modularity of mind. Not offered 2010–11.

HPS/Pl 136. Ethics in Research. *4 units (2-0-2) or 9 units (2-0-7); third term.* Course will address a number of ethical and philosophical issues arising in scientific research. Among the topics discussed will be the following: fraud and misconduct in science; various theories of the scientific method; the realities of science as practiced in laboratories and the pressures facing scientists in the real world; ethical issues raised by collaborative research; reward and credit in science; responsibilities of mentors, referees, and editors in the conduct of research; the role of government regulation and supervision in dealing with scientific misconduct; the role of the university; and changes in ethical standards due to advancing technology. Undergraduates wishing to take the course for advanced humanities credit should register for 9 units (a term paper will be required). Students who register for 4 units may do so on a pass/fail basis only. Not offered 2010–11.

HPS/Pl 137. Experimental Philosophy. *9 units (3-0-6); third term.* A survey of recent work in experimental philosophy: experimental studies aimed at advancing debates in a number of areas of philosophy including metaphysics, semantics, epistemology, philosophy of science, and ethics. Not offered 2010–11.

HPS/Pl 138. Human Nature and Society. *9 units (3-0-6).* This course will investigate how assumptions about human nature shape political philosophy, social institutions, and social policy. The course will begin with a historical perspective, examining the work of such political philosophers as Plato, Locke, Rousseau, and Marx, along with such psychologists as Freud and Skinner. Against this historical perspective, it will then turn to examine contemporary views on human nature from cognitive neuroscience and evolutionary psychology and explore their potential implications for political philosophy and social policy. Among topics to be discussed will be the nature of human sociality and cooperation; economic systems and assumptions regarding production and consumption; and propaganda, marketing, and manipulation. Not offered 2010–11.

HPS/H 156. The History of Modern Science. *9 units (3-0-6); third term.* Selected topics in the development of the physical and biological sciences since the 17th century. Instructor: Heilbron.

Pl/HPS 157. Leibniz vs. Newton: Philosophers at War. *9 units (3-0-6).* For course description, see Philosophy.

HPS/H 158. The Scientific Revolution. *9 units (3-0-6); second term.* The birth of modern Western science from 1400 to 1700. The course examines the intellectual revolution brought about by the contributions of Copernicus, Galileo, Descartes, Kepler, Newton, and Harvey, and their relation to major political, social, and economic developments. Not offered 2010–11.

HPS/H 159. The Cold War and American Science. *9 units (3-0-6).* This course examines the growth of science in America after World War II, and its relation to Cold War geopolitics. Topics will include the growth of the American research university; the establishment and role of the national laboratory system; the role of federal funding agencies including ONR, NSF, NIH, and DARPA; and the impact of geopolitical considerations and priorities on scientific research and knowledge. Not offered 2010–11.

HPS/H 160 ab. Einstein and His Generation: The History of Modern Physical Sciences. *9 units (3-0-6); first, third terms.* An exploration of the most significant scientific developments in the physical sciences, structured around the life and work of Albert Einstein (1879–1955), with particular emphasis on the new theories of radiation, the structure of matter, relativity, and quantum mechanics. While using original Einstein manuscripts, notebooks, scientific papers, and personal correspondence, we shall also study how experimental and theoretical work in the sciences was carried out; scientific education and career patterns; personal, political, cultural, and sociological dimensions of science. Not offered 2010–11.

HPS/H 162. Social Studies of Science. *9 units (3-0-6), third term.* A comparative, multidisciplinary course that examines the practice of science in a variety of locales, using methods from the history, sociology, and anthropology of scientific knowledge. Topics covered include the high-energy particle laboratory as compared with a biological one; Western as compared to non-Western scientific reasoning; the use of visualization techniques in science from their inception to virtual reality; gender in science; and other topics. Not offered 2010–11.

HPS/H 166. Historical Perspectives on the Relations between Science and Religion. *9 units (3-0-6); first term.* The course develops a framework for understanding the changing relations between science and religion in Western culture since antiquity. Focus will be on the ways in which the conceptual, personal, and social boundaries between the two domains have been reshaped over the centuries. Questions to be addressed include the extent to which a particular religious doctrine was more or less amenable to scientific work in a given period, how scientific activity carved an autonomous domain, and the roles played by scientific activity in the overall process of secularization. Instructor: Hubner.

HPS/H 167. Experimenting with History/Historic Experiment. *9 units (3-0-6); third term.* This course uses a combination of lectures with hands-on laboratory work to bring out the methods, techniques, and knowledge that were involved in building and conducting historical experiments. We will connect our laboratory work with the debates and claims made by the original discoverers, asking such questions as how experimental facts have been connected to theories, how anomalies arise and are handled, and what sorts of conditions make historically for good data. Typical experiments might include investigations of refraction, laws of electric force, interference of polarized light, electromagnetic induction, or resonating circuits and electric waves. We will reconstruct instrumentation and experimental apparatus based on a close reading of original sources. Instructor: J. Buchwald.

HPS/H 168. History of Electromagnetism and Heat Science. *9 units (3-0-6); offered by announcement.* This course covers the development of electromagnetism and thermal science from its beginnings in the early 18th century through the early 20th century. Topics covered include electrostatics, magnetostatics, electrodynamics, Maxwell's field theory, the first and second laws of thermodynamics, and statistical mechanics as well as related experimental discoveries. Not offered 2010–11.

HPS/H 169. Selected Topics in the History of Science and Technology. *9 units (3-0-6); offered by announcement.* Instructors: D. Buchwald, visiting lecturers.

HPS/Pl 169. Selected Topics in Philosophy of Science. *9 units (3-0-6); offered by announcement.* Instructors: Staff, visiting lecturers.

HPS/H 170. History of Light from Antiquity to the 20th Century. *9 units (3-0-6); second term.* A study of the experimental, mathematical, and theoretical developments concerning light, from the time of Ptolemy in the 2nd century A.D. to the production of electromagnetic optics in the 20th century. Instructor: J. Buchwald.

HPS/H 171. History of Mechanics from Galileo through Euler. *9 units (3-0-6); second term. Prerequisite: basic Caltech physics course.* This course covers developments in mechanics, as well as related aspects of mathematics and models of nature, from just before the time of Galileo through the middle of the 18th century, which saw the creation of fluid and rotational dynamics in the hands of Euler and others. Not offered 2010–11.

HPS/H 172. History of Mathematics: A Global View with Close-ups. *9 units (3-0-6); offered by announcement.* The course will provide students with a brief yet adequate survey of the history of mathematics, characterizing the main developments and placing these in their chronological, cultural, and scientific contexts. A more detailed study of a few themes, such as Archimedes' approach to infinite processes, the changing meanings of "analysis" in mathematics, Descartes' analytic geometry, and the axiomatization of geometry c. 1900; students' input in the choice of these themes will be welcomed. Not offered 2010–11.

HPS/H/Pl 173. History of Chemistry. *9 units (3-0-6); first term.* This course examines developments in chemistry from medieval alchemy to the time of Lavoisier. It will examine the real content of alchemy and its contributions to modern science, as well as how to decode its bizarre language; chemistry's long quest for respect and academic status; the relations of chemistry with metallurgy, medicine, and other fields; and the content and development of the chemical theories and the chemical laboratory and its methods. Not offered 2010–11.

HPS/H 174. Early Greek Astronomy. *9 units (3-0-6); third term.* The course will highlight the background and some of the landmarks in the evolution of Greek astronomy from its tentative beginnings in the 5th century B.C., to its culmination in the work of Ptolemy in the 2nd century A.D. Not offered 2010–11.

HPS/H 175. Matter, Motion, and Force: Physical Astronomy from Ptolemy to Newton. *9 units (3-0-6); second term.* The course will examine how elements of knowledge that evolved against significantly different cultural and religious backgrounds motivated the great scientific revolution of the 17th century. Not offered 2010–11.

HPS/H 178. Galileo's Astronomy and Conflicts with the Church. *9 units (3-0-6); second term*. Galileo's discoveries with the telescope and arguments for the heliocentric theory radically transformed the System of the World, as it was called, and resulted in his being brought before the Inquisition, the most famous single event in the history of science. The readings will be Galileo's *Sidereal Messenger*, *Letters on Sunspots*, *The Assayer*, *Dialogue on the Two Great Systems of the World*, and documents concerned with Galileo's conflicts with the Church in 1616 and 1633. Not offered 2010–11.

HPS/H 179. Cambridge Scientific Minds: How We See Them; How They See Themselves. *9 units (3-0-6).* Cambridge University has long been a world center for science. Using biography, autobiography, novel, and historical studies, this course will examine and analyze the thought of Newton, Darwin, Maxwell, Watson, Crick, and Hawking. Not offered 2010–11.

HPS/H 180. Physics and Philosophy from the Scientific Revolution to the 20th Century. *9 units (3-0-6).* This course will examine the interplay between the theoretical understanding of physical nature and the philosophical definition of reliable knowledge. It will investigate this intellectual interplay in the work of Galileo, Descartes, Newton, Hume, Maxwell, and Einstein. Not offered 2010–11.

HPS/H 181. Evidence, Measurement, and the Uses of Data in the Early Modern Period. *9 units (3-0-6).* From treatises about geography and astronomy to the history of plants and animals, early modern Natural philosophy provided an astonishingly broad background of research agendas. The course will examine the manner in which observations were carried out and evidence weighed, both in university settings and in the field. Topics to be addressed include the changing perceptions regarding the reliability of the senses; the contribution of instruments to accumulation of reliable knowledge; the standardization of data and its presentation; and the emergence of new argumentative strategies. Not offered 2010–11.

HPS/H 182. Show and Tell: 3-D Models for the Visualization of Complex Concepts in the 16th and 17th Centuries. *9 units (3-0-6).* Early modern artists and scholars of all disciplines routinely built three-dimensional objects in order to represent complex concepts and appearances. Some rendered visible abstract formulas in geometrical forms like the movement of the stars; others schematized complex work-flows like drainage systems, or the geographical conditions on Earth; still others proposed costly projects, such as the cupola of St. Peter in Rome, on the basis of a model. These models—many of which still survive—were constructed according to precise rules and regulations, as well as personal taste. The course will offer an introduction to the significance of three-dimensional models in the early modern period, and the manner in which they were crafted and used by artists, physicians, and natural philosophers. Not offered 2010–11.

Pl/HPS 183. Bioethics. *9 units (3-0-6).* For course description, see Philosophy.

Pl/HPS 184. Science, Ethics, and Public Policy. *9 units (3-0-6).* For course description, see Philosophy.

H/HPS 184. Medicine and Disease from Antiquity to the Nineteenth Century. *9 units (3-0-6).* For course description, see History.

H/HPS 185. Angels and Monsters. *9 units (3-0-6).* For course description, see History.

HPS/H 186. The Sciences in the Romantic Era. *9 units (3-0-6); second term.* This course aims at introducing students to problems, methods, and resources in European science during the era of Romanticism (c. 1780–1830). The Romantic movement embraced the sciences as well as literature, theology, and the arts, and sought to unite them into a comprehensive program of understanding nature based on experimentation and speculative philosophy. Scientists of the Romantic era have addressed fundemental concerns about scientific manipulations of nature that have, in a different form, resurfaced in the later part of the 20th century. Romanticism addresses major themes in the self-awareness of scientists and their perception in society, and it contributed to the emergence of new research fields and scientific institutions to accommodate nationalistic claims. Instructor: Hubner.

HPS/Pl 188. The Evolution of Cognition. *9 units (3-0-6); third term.* By many measures, *Homo sapiens* is the most cognitively sophisticated animal on the planet. Not only does it live in a huge variety of habitats, and not only has it transformed its environment in unprecedented ways, but it is also responsible for such cultural artifacts as language, science, religion, and art. These are achievements that other species, however successful they may be in other respects, have not accomplished. This course investigates the cognitive, behavioral, and environmental bases for humans' surprising cultural dominance of our planet. Possible topics include the evolution of language, the evolution of morality, the evolution of religion, the evolution of cooperation, and the advent of technology, math, science, and the Internet. Contact the instructor to find out what the topic in any given term is. Instructor: Cowie.

HUMANITIES

Hum/H 1 ab. East Asian History. *9 units (3-0-6); offered by announcement.* Late imperial values, institutions, and behaviors and their evolution in the 19th and 20th centuries. Hum/H 1 a will deal largely with China, and Hum/H 1 b with Japan. The readings will consist of selected thematic texts as well as a chronological textbook. Each term is independent of the other, and students will normally take only one of the two terms. Not offered 2010–11.

Hum/H 2. American History. *9 units (3-0-6); first term.* Among the major events, trends, and problems of our country's history are the American Revolution, the framing and development of the Constitution, wars, slavery and emancipation, ethnic and gender relations, immigration, urbanization, westward conquest, economic fluctuations, changes in the sizes and functions of governments, foreign relations, class conflicts, domestic violence, and social and political movements. Although no one course can treat all of these themes, each freshman American history course will deal with two or more of them. How have American historians approached them? What arguments and evidence have scholars offered for their interpretations and how can we choose between them? In a word, what can we know about our heritage? Instructor: Kousser.

Hum/H 3 abc. European Civilization. *9 units (3-0-6); offered by announcement.* This course will be divided into three terms, each of which will focus on a coherent period in the history of European civilization. Each term is independent of the others, and students will normally take only one of the three terms.

a. The Classical and Medieval Worlds. Will survey the evolution of Mediterranean and European civilization from antiquity through the end of the Middle Ages. It will emphasize the reading and discussion of primary sources, especially but not exclusively literary works, against the backdrop of the broad historical narrative of the periods. The readings will present students with the essential characteristics of various ancient and medieval societies and give students access to those societies' cultural assumptions and perceptions of change. Instructors: Archambeau, Brown, Clark.

b. Early Modern Europe. Will survey the evolution of European civilization from the 14th century to the early 19th century. The topics covered will depend on the individual instructor, but they will include some of the major changes that transformed Western civilization in the early modern period, such as the Renaissance, the Reformation, the rise of sovereign states and the concomitant military revolution, the Scientific Revolution and the Enlightenment, and the French and industrial revolutions. Readings will include major works from the period, as well as studies by modern historians. Instructors: Brewer, Dennison, Gomez, M. Hunter.

c. Modern Europe. Will introduce students to major aspects of the politics and culture of modernity that have profoundly transformed Western society and consciousness from the French Revolution to the contemporary era. A variety of historical, literary, and artistic works will be used to illuminate major social, intellectual, and cultural movements. The focus will be on significant and wide-ranging historical change (e.g., the industrial revolution, imperialism, socialism, fascism); on cultural innovation (e.g., modernism, impressionism, cubism); and on the work of significant thinkers. Instructors: Kormos-Buchwald, Rosenstone.

Hum/H 4 abc. Civilization, Science, and Archaeology. *9 units (3-0-6); offered by announcement.* This course will be divided into three terms, each of which will focus on a particular aspect of pre-classical antiquity or premodern science. Each term is independent of the others, and students will normally take only one of the three terms. Instructor: Buchwald.

a. Before Greece: The Origins of Civilization in Mesopotamia. This course will introduce students to the early development of civilization in Mesopotamia and Egypt from 4000 B.C.E. through 1000 B.C.E. Origins of agriculture and writing, the evolution of the city, and the structures of the Mesopotamian economy and social order will be discussed. Comparison with contemporary developments in Egypt during the Old and Middle Kingdoms may include a reading of

Gilgamesh from 3000 B.C.E. and of the Egyptian *Tale of Sinuhe*. The course concludes with a discussion of life during the late Bronze Age. Focus will be on life as it was lived and experienced by many groups in pre-classical antiquity rather than on kings and dynasties. Instructor: J. Buchwald.

b. The Development of Science from Babylon through the Renaissance. Connections in antiquity between astrology and astronomy, early theories of light, Islamic science, new concepts of knowledge during the European Middle Ages and Renaissance, the early laboratory, the development of linear perspective, the origins of the Copernican and Keplerian systems of astronomy, and the science of Galileo.

c. The Origins of Polytheism and Monotheism in Ancient Egypt, Mesopotamia, and Israel and the Nature of Religious Belief. The civilizations of Egypt and Mesopotamia gave rise to complex forms of religious practices connected to the social order, moral behavior, and the afterlife. The course examines the origins of concepts of moral death and of sin as a violation of cosmic order in antiquity, the nature of polytheism, and the manner in which monotheism arose out of it. In addition to historical analyses the course includes readings by anthropologists who have studied cult structures as well as contemporary theories by evolutionary psychologists. Instructor: J. Buchwald.

Hum/En 5. Major British Authors. *9 units (3-0-6); offered by announcement.* This course will introduce students to one or more of the genres of English literature, including poetry, drama, and prose fiction, by studying major authors from different periods. Sometimes the course will cover a wide range of authors, while at others it will concentrate on a few. Authors might include Chaucer, Shakespeare, Milton, Austen, George Eliot, or Joyce. Instructors: Gilmore, Haugen.

Hum/En 6. American Literature and Culture. *9 units (3-0-6); offered by announcement.* Studies of American aesthetics, genres, and ideas from the birth of the nation to the present. Students will be introduced to the techniques of formal analysis. We will consider what constitutes evidence in relation to texts and how to develop a persuasive interpretation. Topics may include *Nature's Nation*, slavery and its aftermath, individualism and the marketplace, the "New Woman," and the relation between word and image. Instructors: C. Hunter, Weinstein.

Hum/En 7. Modern European Literature. *9 units (3-0-6); offered by announcement.* An introduction to literary analysis through a sustained exploration of the rise and aftermath of modernism. What was the modernist revolt of the early 20th century, how did it challenge literary tradition and existing social forms, and to what extent have we inherited a world remade by modernism? While the course will focus on British and Continental literature, writers from other parts of the world whose work closely engages the European tradition may also be considered. Authors may include Flaubert, James, Conrad, Joyce, Woolf, Kafka, Borges, Yeats, and Eliot. Instructor: Gilmartin.

Hum/Pl 8. Right and Wrong. *9 units (3-0-6); offered by announcement.* This course addresses questions such as: Where do our moral ideas come from? What justifies them? How should they guide our conduct, as individuals and as a society? What kind of person should one aspire to be? Topics the course may deal with include meta-ethical issues (e.g., What makes an action right or wrong? When is one morally responsible for one's actions? How should society be organized?) and normative questions (e.g., Is eating meat morally acceptable? What should we tolerate and why? What are society's obligations toward the poor?). In addition, the psychological and neural substrates of moral judgment and decision making may be explored. The course draws on a variety of sources, including selections from the great works of moral and political philosophy (e.g., Aristotle's *Nichomachean Ethics*, Hobbes's *Leviathan*, Kant's *Groundings for a Metaphysics of Morals*, and Rawls's *A Theory of Justice*), contemporary discussions of particular moral issues, and the science of moral thought. Instructors: Quartz, Cowie.

Hum/Pl 9. Knowledge and Reality. *9 units (3-0-6); offered by announcement.* The theme of this course is the scope and limitations of rational belief and knowledge. Students will examine the nature of reality, the nature of the self, the nature of knowledge, and how we learn about the natural world. Students will be introduced to these issues through selections from some of the world's greatest philosophical works, including Descartes's *Meditations*, Pascal's *Pensées*, Hume's *Enquiry Concerning Human Understanding*, Berkeley's *Principles of Human Knowledge*, and Kant's *Prolegomena to any Future Metaphysics.* A variety of more contemporary readings will also be assigned. Instructors: Stan, Hitchcock, Manning.

Hum/H/HPS 10. Introduction to the History of Science. *9 units (3-0-6); offered by announcement.* Major topics include the following: What are the origins of modern Western science, when did it emerge as distinct from philosophy and other cultural and intellectual productions, and what are its distinguishing features? When and how did observation, experiment, quantification, and precision enter the practice of science? What were some of the major turning points in the history of science? What is the changing role of science and technology? Using primary and secondary sources, students will take up significant topics in the history of science, from ancient Greek science to the 20th-century revolution in physics, biology, and technology. Hum/H/HPS 10 may be taken for credit toward the additional 36-unit HSS requirement by HPS majors and minors who have already fulfilled their freshman humanities requirement and counts as a history course in satisfying the freshman humanities breadth requirement. Instructors: Heilbron, Hubner.

Hum/H/HPS 11. History of Astronomy and Cosmology. *9 units (3-0-6); offered by announcement.* A consideration of the entire history of astronomy and cosmology, the oldest of all the sciences, from antiquity to the late 20th century, from the Babylonians to the Big Bang. The course will be devoted to repeating the procedures used in earlier astronomy and working directly with the primary sources. Not offered 2010–11.

F/Hum 32. Humanities on Film. *3 units (1-1-1).* For course description, see Film.

Hum 119. Selected Topics in Humanities. *9 units (3-0-6); offered by announcement.* Instructors: Staff, visitors.

INDEPENDENT STUDIES PROGRAM

Students who have chosen to enter the Independent Studies Program (ISP) instead of a formulated undergraduate option may enroll in special ISP courses. These courses are designed to accommodate individual programs of study or special research that fall outside ordinary course offerings. The student and the instructor first prepare a written course contract specifying the work to be accomplished and the time schedule for reports on progress and for work completed. The units of credit and form of grading are decided by mutual agreement between the instructor, the student, and his or her advisory committee. See page 224 for complete details.

INFORMATION SCIENCE AND TECHNOLOGY

IST 1. Introduction to Information. *9 units (3-0-6); third term.* This course offers an introduction to the modern study of information, addressing fundamental questions about information representation, transmission, and learning. Questions considered include: What is information, and how should we represent it for storage and transmission? What does it mean to represent information efficiently? Is there a "shortest possible" description? Can we hope to communicate reliably in a noisy world? How much information can be transmitted, and what are the strategies by which we can improve reliability? What does it mean for a machine to learn? How much data must be observed to achieve reliable learning? Not offered on a pass/ fail basis. *Satisfies the menu requirement of the Caltech core curriculum.* Not offered 2010–11.

IST 4. Information and Logic. *9 units (3-0-6); third term.* The course explains the key concepts at the foundations of computing with physical substrates, including representations of numbers, Boolean algebra as an axiomatic system, Boolean functions and their representations, composition of functions and relations, implementing functions with circuits, circuit complexity, representation of computational processes with state diagrams, state diagrams as a composition of Boolean functions and memory, and the implementation of computational processes with finite state machines. The basic concepts covered in the course are connected to advanced topics like programming, computability, logic, complexity theory, information theory, and biochemical systems. Not offered on a pass/fail basis. *Satisfies the menu requirement of the Caltech core curriculum.* Instructor: Bruck.

LANGUAGES

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L 1. Selected Topics in Language. *Units to be determined by arrangement with the instructor.* Graded pass/fail. Instructors: Staff, visiting lecturers.

L 60 ab. German Literature in Translation. *9 units (3-0-6).* First term: "Tales of Hollywood," German exile literature 1933–45; second term: German literature of the 19th century—Biedermeier, young Germany, realism, and naturalism. Not offered 2010–11.

L 102 abc. Elementary French. *9 units (3-0-6); first, second, third terms.* The course uses French in Action, a multimedia program, and emphasizes the acquisition of fundamental skills: oral ability, comprehension, writing, and reading. Students are evaluated on the basis of quizzes and compositions (1/3), midterm and final (1/3), and class participation (1/3). The course is mainly designed for students with no previous knowledge of French. Students who have had French in secondary school or college must consult with the instructor before registering. Instructor: Orcel.

L 103 abc. Intermediate French. *9 units (3-0-6); first, second, third terms. Prerequisite: L 102 abc or equivalent.* The first two terms feature an extensive grammar review and group activities that promote self-expression. Op-Ed articles and a series of literary texts provide a basis for classroom discussion and vocabulary expansion. Several short written compositions are required. The third term is designed to further develop an active command of the language. A variety of 19th- and 20th-century short stories are discussed in class to improve comprehension and oral proficiency. Students are expected to do an oral presentation, to write four short compositions, and a final paper. Second and third terms are offered for advanced humanities credit. Instructors: de Bedts, Orcel.

L/F 104. French Cinema. *9 units (3-0-6); first term. Prerequisite: L 103 abc or equivalent.* A critical survey of major directors, genres, and movements in French cinema. Particular attention is devoted to the development of film theory and criticism in France and their relation to film production. The course may also focus on problems of transposition from literature to cinema. The course includes screenings of films by Melies, Dulac, Clair, Renoir, Carné, Pagnol, Cocteau, Bresson, Tati, Truffaut, Godard, Resnais, Lelouch, Malle, Pialat, Rohmer, and Varda. Students are expected to write three 5-page critical papers. Conducted in French. Not offered 2010–11.

L 105 ab. Topics in French Culture and Literature. *9 units (3-0-6); second term. L 105 a and L 105 b taught in alternate years. Prerequisite: L 103 abc or equivalent.* Part a: 20th-century French literature. Part b: Contemporary France. Conducted in French. Offered for advanced humanities credit. Instructor: Orcel.

L 106 abc. Elementary Japanese. *9 units (5-0-4); first, second, third terms.* Emphasis on oral-aural skills, and understanding of basic grammar. Immediate introduction of the native script—*hiragana*, *katakana*—and gradual introduction to 300 to 500 characters. Not offered on a pass/fail basis. Instructor: Hirai.

L 107 abc. Intermediate Japanese. *10 units (5-1-4); first, second, third terms. Prerequisite: L 106 abc or equivalent.* Continued instruction and practice in conversation, building up vocabulary, and understanding complex sentence patterns. The emphasis, however, will be on developing reading skills. Recognition of approximately 1,000 characters. Not offered on a pass/fail basis. Instructor: Hirata.

L 108 abc. Advanced Japanese. *10 units (3-1-6); first, second, third terms. Prerequisite: L 107 abc or equivalent.* Developing overall language skills. Literary and newspaper readings. Technical and scientific translation. Improvement of listening and speaking ability so as to communicate with Japanese people in real situations. Recognition of the 1,850 "general-use characters." Not offered on a pass/fail basis. Instructor: Hirata.

L/F 109. Introduction to French Cinema from Its Beginning to the Present. *9 units (3-0-6); first term.* This course will introduce students to the artistic style and the social, historical, and political content of French films, starting with Méliès and the Lumière brothers and working through surrealism and impressionism, 1930s poetic realism, the Occupation, the New Wave, the *Cinema du look*, and the contemporary cinema. The class will teach students to look at film as a medium with its own techniques and formal principles. Conducted in English. Instructor: Orcel.

L 110 abc. Elementary Spanish. *9 units (3-0-6); first, second, third terms.* Grammar fundamentals and their use in understanding, speaking, reading, and writing Spanish. Exclusively for students with no previous knowledge of Spanish. Instructors: Garcia, Arjona.

L 112 abc. Intermediate Spanish. *9 units (3-0-6); first, second, third terms. Prerequisite: L 110 abc or equivalent.* Grammar review, vocabulary building, practice in conversation, and introduction to relevant history, literature, and culture. Literary reading and writing are emphasized in the second and third terms. Students who have studied Spanish elsewhere must consult with the instructor before registering. Instructors: Garcia, Arjona.

L 114 abc. Spanish and Latin American Literature. *9 units (3-0-6); first, second, third terms. Prerequisite: L 112 abc or equivalent.* First and second terms: study of literary texts from the Spanish American and Spanish traditions, their cultural and historical relevance, covering all periods, with emphasis on contemporary authors. Third term: contemporary topics in literature and/or film of the Hispanic world. Conducted in Spanish. Instructor: Garcia.

L 130 abc. Elementary German. *9 units (3-0-6); first, second, third terms.* Grammar fundamentals and their use in aural comprehension, speaking, reading, and writing. Students who have had German in secondary school or college must consult with the instructor before registering. Instructor: Aebi.

L 132 abc. Intermediate German. *9 units (3-0-6); first, second, third terms. Prerequisite: L 130 abc or equivalent.* Reading of short stories and plays, grammar review, aural and oral drills and exercises, expansion of vocabulary, and practice in reading, writing, and conversational skills. Second and third terms will emphasize written expression, technical/scientific translation, and literary readings. Students who have studied German elsewhere must consult with the instructor before registering. Instructor: Aebi.

L 140 abc. German Literature. *9 units (3-0-6). Prerequisite: L 132 c or equivalent (two years of college German), or instructor's permission.* Reading and discussion of works by selected 12th–21st-century authors, current events on Internet/TV, exposure to scientific and technical writing, business communication. Viewing and discussion of German-language films. Conducted in German. Not offered 2010–11.

H/L 142. Perspectives on History through Russian Literature. *9 units (3-0-6).* For course description, see History.

L 152 ab. French Literature in Translation: Classical and Modern. *9 units (3-0-6); first, third terms.* First term: French classical literature of the 17th and 18th centuries; third term: reading and discussion of works by selected 19th- and 20th-century authors. The approach is both historical and critical. Conducted in English, but students may read the French originals. Film versions of the texts studied may be included. Instructor: de Bedts.

L 162. Spanish and Latin American Literature in Translation. *9 units (3-0-6); offered by announcement.* This class is an introduction to the literary masterworks of the Hispanic tradition from the 16th to the 20th centuries. Readings and discussions are in English, but students may read Spanish originals. Instructor: Staff.

L 167 abc. Latin Literature. *9 units (3-0-6); first, third terms. Prerequisite: three years of high-school Latin.* Major works of Latin literature, usually one per term. No work will be studied more than once in four years, and students may repeat the course for credit. Instructor: Pigman.

L 170 abc. Introduction to Chinese. *10 units (4-1-5); first, second, third terms.* An introductory course in standard Chinese (Mandarin) designed for students with no previous knowledge of the language. The course introduces the fundamentals of Chinese, including pronunciation, grammar, and Chinese characters, emphasizing the four basic language skills: listening, speaking, reading, and writing. By the end of the three-term sequence, students will have acquired knowledge of basic rules of grammar and the ability to converse, read, and write on simple topics of daily life, and will have command of more than 800 Chinese compounds and 700 characters. Instructor: Wang.

L 171 abc. Elementary Chinese. *9 units (5-0-4); first, second, third terms. Prerequisite: placement exam results or instructor's permission.* A fast-paced course for students who have had prior exposure to the language. Students are introduced to the basic principles of written and oral communication. Emphasis will be placed on consolidating basic grammar, and developing the ability to use the language creatively in talking about oneself and in dealing with daily situations within a Chinese cultural context. Instructor: Ming.

L 172 abc. Intermediate Chinese. *10 units (4-1-5); first, second, third terms. Prerequisite: L 170 abc or L 171 abc or equivalent.* A course designed to meet the personal interests and future professional goals of students who have had one year of elementary modern Chinese. Students will learn new vocabulary, sentence patterns, idiomatic expressions, and proverbs, as well as insights into Chinese society, culture, and customs. Instructor: Wang.

L 173 ab. Advanced Chinese. *10 units (3-1-6); first, second terms. Prerequisite: L 172 abc or equivalent.* A course designed to further develop overall language proficiency through extensive reading of selected texts representing a wide variety of styles and genres, including newspapers and magazines, visual materials, and a selection of works of major modern writers. Classes are conducted primarily in Chinese. Instructor: Ming.

L 174. Topics in Chinese Literature. *9 units (3-0-6); third term. Prerequisite: instructor's permission.* Reading and discussion of representative Chinese works from the 16th century to the present, including contemporary works from China, Taiwan, and Hong Kong. Conducted in Chinese. Students are expected to examine literary works in light of their sociopolitical and historical contexts. Instructor: Ming.

LAW

Law 33. Introduction to the Law. *9 units (3-0-6); first term.* An introduction to Anglo-American law from both the legal and the social-scientific points of view. Subject can vary from year to year. Available for introductory social science credit. Instructor: McCaffery.

Law 134. Law and Technology. *9 units (3-0-6); third term.* A sophisticated introduction to and exploration of the intersection of science and the law, focusing on the intellectual property system and the various means by which the conduct and products of scientific research are regulated. The course will analyze and compare American, international, and theoretical alternative systems, in part by means of economics modeling. The latter portion of the course will explore a particular scientific area in depth, typically using guest lecturers or coteachers to convey the science element (examples include the human genome project; the Internet and cyberspace; the law of the sea; and outer-space exploration). Some background in law and economics would be helpful. Instructor: McCaffery.

Law 135. History of Anglo-American Law. *9 units (3-0-6); second term.* An introductory survey of English law from medieval to modern times, with discussion of parallel and divergent developments in the United States. Topics include the constitution: constraints on the king, Magna Carta, the rise of parliamentary democracy, the role of courts, written versus unwritten constitutions, the U.S. Constitution; law making: statutes and the doctrine of precedent; fact finding: trial by battle and by ordeal, the development of the jury trial; civil justice: common law, equity, contract, and property law; criminal justice: private and public prosecution, star chamber, defendants' rights, criminal sanctions; family law and the changing legal status of women. Not offered 2010–11.

Law/PS/H 148 ab. The Supreme Court in U.S. History. *9 units (3-0-6); second, third terms.* The development of the Supreme Court, its doctrines, personalities, and role in U.S. history through analyses of selected cases. The first half of the course, which is a prerequisite for the second half but may also be taken by itself, will deal with such topics as federalism, economic regulation, political rights, and free speech. The second half will cover such issues as the rights of the accused, equal protection, and privacy. Instructor: Kousser.

MATERIALS SCIENCE

MS 78 abc. Senior Thesis. *9 units; first, second, third terms. Prerequisite: instructor's permission.* Supervised research experience, open only to senior materials science majors. Starting with an open-ended topic, students will plan and execute a project in materials science and engineering that includes written and oral reports based upon actual results, synthesizing topics from their course work. Only the first term may be taken pass/fail. Instructor: Staff.

MS 90. Materials Science Laboratory. *9 units (1-6-2); third term.* An introductory laboratory in relationships between the structure and properties of materials. Experiments involve materials processing and characterization by X-ray diffraction, scanning electron microscopy, and optical microscopy. Students will learn techniques for measuring mechanical and electrical properties of materials, as well as how to optimize these properties through microstructural and chemical control. Independent projects may be performed depending on the student's interests and abilities. Instructor: Staff.

MS 100. Advanced Work in Materials Science. The staff in materials science will arrange special courses or problems to meet the needs of students working toward the M.S. degree or of qualified undergraduate students. Graded pass/fail for research and reading. Instructor: Staff.

MS 105. Phase Transformations. *9 units (3-0-6); third term. Prerequisite: APh 105 b or ChE/Ch 164, or instructor's permission.* Thermodynamics and kinetics of phase transformations. Phase diagrams for decomposition and ordering. Nucleation, spinodal decomposition, microstructural morphologies. Role of strain energy in solid-solid phase transformations. Thermomechanical processing of selected materials. Taught concurrently with APh 105 c. Instructor: Fultz.

MS 110 abc. Materials Research Lectures. *1 unit; first, second, third terms.* A seminar course designed to introduce advanced undergraduates and graduate students to modern research in materials science. Instructor: Snyder.

MS 115 ab. Fundamentals of Materials Science. *9 units (3-0-6); first, second terms. Prerequisite: Ph 2.* An introduction to the structure and properties of materials and the processing routes utilized to optimize properties. All major classes of materials are covered, including metals, ceramics, electronic materials, composites, and polymers. In the first term, emphasis is on the relationships between chemical bonding, crystal structure, thermodynamics, phase equilibria, microstructure, and properties. In the second term, generic processing and manufacturing methods are presented for each class of materials with particular focus on the influence of these processes on mechanical properties. Emphasis is placed on the basic materials science behind each processing method, covering such topics as thermodynamics, diffusion, kinetics of phase transformations, and microstructure development. Instructors: Haile, van de Walle.

MS 125. Advanced Transmission Electron Microscopy. *9 units (1-6-2); third term. Prerequisite: MS 132.* Diffraction contrast analysis of crystalline defects. Phase contrast imaging. Physical optics approach to dynamical electron diffraction and imaging. Microbeam methods for diffraction and imaging. Chemical analysis by energy dispersive X-ray spectrometry and electron energy loss spectrometry. Instructor: Ahn.

MS 130. Diffraction and Structure. *9 units (3-0-6); first term. Prerequisite: graduate standing or instructor's permission.* Content is identical to MS 132 but without the laboratory exercises. Instructor: Fultz.

MS 131. Structure and Bonding in Materials. *9 units (3-0-6); second term. Prerequisite: graduate standing or introductory quantum mechanics.* Atomic structure, hybridization, molecular orbital theory, dependence of chemical bonding on atom configurations. Covalency, ionicity, electronegativity. Madelung energy. Effects of translational periodicity on electron states in solids. Band structures of group IV semiconductors; transition metals and ferromagnetism. Structural features of materials such as point defects, dislocations, disclinations, and surfaces. Structures of defects calculated with the embedded atom method. Instructor: van de Walle.

MS 132. Diffraction and Structure of Materials. *12 units (3-3-6); first term.* Principles of electron and X-ray diffraction, with applications for characterizing materials. Topics include scattering and absorption of electrons and X rays by atoms. The transmission electron microscope (TEM) and the X-ray diffractometer. Kinematical theory of diffraction: effects of strain, size, disorder, and temperature. Crystal defects and their characterization. A weekly laboratory will complement the lectures. Instructors: Fultz, Ahn.

MS 133. Kinetic Processes in Materials. *9 units (3-0-6); third term. Prerequisite: APh 105 b or ChE/Ch 164, or instructor's permission.* Kinetic master equation, uncorrelated and correlated random walk, diffusion. Mechanisms of diffusion and atom transport in solids, liquids, and gases. Coarsening of microstructures. Nonequilibrium processing of materials. Instructors: Greer, Kornfield.

MS 142. Application of Diffraction Techniques in Materials Science. *9 units (2-3-4); third term. Prerequisite: MS 132 or instructor's permission.* Applications of X-ray and neutron diffraction methods to the structural characterization of materials. Emphasis is on the analysis of polycrystalline materials but some discussion of single crystal methods is also presented. Techniques include quantitative phase analysis, crystalline size measurement, lattice parameter refinement, internal stress measurement, quantification of preferred orientation (texture) in materials, Rietveld refinement, and determination of structural features from small angle scattering. Homework assignments will focus on analysis of diffraction data. Samples of interest to students for their thesis research may be examined where appropriate. Not offered 2010–11.

MS/EST 143. Solid-State Electrochemistry for Energy Storage and Conversion. *9 units (3-0-6); third term.* Thermodynamics and kinetics of ion and electron transport in solids, with emphasis on processes in electrolyte and electrode materials used in energy storage and conversion. Treatment of electroanalytical characterization techniques including a.c. impedance spectroscopy, voltammetry, and d.c. polarization methods. Application areas include fuel cells, electrochemical gas separation membranes, batteries, supercapacitors, and hydrogen storage materials. Instructor: Haile.

MS 150 abc. Topics in Materials Science. *Units to be arranged; first, second, third terms.* Content will vary from year to year, but will be at a level suitable for advanced undergraduate or graduate students. Topics are chosen according to the interests of students and faculty. Visiting faculty may present portions of the course. Instructor: Staff.

MS/ME 161. Imperfections in Crystals. *9 units (3-0-6); third term. Prerequisite: graduate standing or MS 115 a.* The relation of lattice defects to the physical and mechanical properties of crystalline solids. Introduction to point imperfections and their relationships to transport properties in metallic, covalent, and ionic crystals. Kroeger-Vink notation. Introduction to dislocations: geometric, crystallographic, elastic, and energetic properties of dislocations. Dislocation reactions and interactions including formation of locks, stacking faults, and surface effects. Relations between collective dislocation behavior and mechanical properties of crystals. Introduction to computer simulations of dislocations. Grain boundaries. The structure and properties of interfaces in solids. Emphasis on materials science aspects of role of defects in electrical, morphological, optical, and mechanical properties of solids. Not offered 2010–11.

MS/ME 162. Mechanical Behavior of Materials. *9 units (3-0-6); first term.* Introduction to the mechanical behavior of solids, emphasizing the relationships between microstructure, defects, and mechanical properties. Elastic, anelastic, and plastic properties of crystalline and amorphous materials. Polymer and glass properties: viscoelasticity, flow, and strain-rate dependence. The relationships between stress, strain, strain rate, and temperature for deformable solids. Application of dislocation theory to strengthening mechanisms in crystalline solids. The phenomena of creep, fracture, and fatigue, and their controlling mechanisms. Instructor: Greer.

EST/MS/ME 199. Special Topics in Energy Science and Technology. *Units to be arranged.* For course description, see Energy Science and Technology.

MS 200. Advanced Work in Materials Science. The staff in materials science will arrange special courses or problems to meet the needs of advanced graduate students.

Ae/AM/MS/ME 213. Mechanics and Materials Aspects of Fracture. *9 units (3-0-6).* For course description, see Aerospace.

ME/MS 260 abc. Micromechanics. *12 units (3-0-9).* For course description, see Mechanical Engineering.

MS 300. Thesis Research.

MATHEMATICS

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Ma 1 abc. Calculus of One and Several Variables and Linear Algebra. *9 units (4-0-5); first, second, third terms. Prerequisites: high-school algebra, trigonometry, and calculus. Special section of Ma 1 a, 12 units (5-0-7).* Review of calculus. Complex numbers, Taylor polynomials, infinite series. Comprehensive presentation of linear algebra. Derivatives of vector functions, multiple integrals, line and path integrals, theorems of Green and Stokes. Ma 1 b, c is divided into two tracks: analytic and practical. Students will be given information helping them to choose a track at the end of the fall term. There will be a special section or sections of Ma 1 a for those students who, because of their background, require more calculus than is provided in the regular Ma 1 a sequence. These students will not learn series in Ma 1 a and will be required to take Ma 1 d. Instructors: van de Belt, Ramakrishnan, Wilson, Aschbacher, Marsden/Mantoran, Flach.

Ma 1 d. Series. *5 units (2-0-3); second term only. Prerequisite: special section of Ma 1 a.* This is a course intended for those students in the special calculus-intensive sections of Ma 1 a who did not have complex numbers, Taylor polynomials, and infinite series during Ma 1 a. It may not be taken by students who have passed the regular Ma 1 a. Instructor: Staff.

Ma 2 ab. Differential Equations, Probability and Statistics. *9 units (4-0-5); first, second terms. Prerequisite: Ma 1 abc.* Ordinary differential equations, probability, statistics. Instructors: Marcolli, Makarov, Rains.

Ma 3. Number Theory for Beginners. *9 units (3-0-6); third term.* Some of the fundamental ideas, techniques, and open problems of basic number theory will be introduced. Examples will be stressed. Topics include Euclidean algorithm, primes, Diophantine equations, including $a^n + b^n = c^n$ and $a^2 - db^2 = \pm 1$, constructible numbers, composition of binary quadratic forms, and congruences. Instructor: Staff.

Ma 4. Introduction to Mathematical Chaos. *9 units (3-0-6); third term.* An introduction to the mathematics of "chaos." Period doubling universality, and related topics; interval maps, symbolic itineraries, stable/unstable manifold theorem, strange attractors, iteration of complex analytic maps, applications to multidimensional dynamics systems and real-world problems. Possibly some additional topics, such as Sarkovski's theorem, absolutely continuous invariant measures, sensitivity to initial conditions, and the horseshoe map. Instructor: Marcolli.

Ma 5 abc. Introduction to Abstract Algebra. *9 units (3-0-6); first, second, third terms. Freshmen must have instructor's permission to register.* Introduction to groups, rings, fields, and modules. The first term is devoted to groups and includes treatments of semidirect products and Sylow's theorem. The second term discusses rings and modules and includes a proof that principal ideal domains have unique factorization and the classification of finitely generated modules over principal ideal domains. The third term covers field theory and Galois theory, plus some special topics if time permits. Instructors: Ramakrishnan, Agarwala, Jorza.

Ma/CS 6 abc. Introduction to Discrete Mathematics. *9 units (3-0-6); first, second, third terms. Prerequisite: for Ma/CS 6 c, Ma/CS 6 a or Ma 5 a or instructor's permission.* First term: a survey emphasizing graph theory, algorithms, and applications of algebraic structures. Graphs: paths, trees, circuits, breadth-first and depth-first searches, colorings, matchings. Enumeration techniques; formal power series; combinatorial interpretations. Topics from coding and cryptography, including Hamming codes and RSA. Second term: directed graphs; networks; combinatorial optimization; linear programming. Permutation groups; counting nonisomorphic structures. Topics from extremal graph and set theory, and partially ordered sets. Third term: elements of computability theory and computational complexity. Discussion of the P=NP problem, syntax and semantics of propositional and first-order logic. Introduction to the Gödel completeness and incompleteness theorems. Instructors: Wilson, Balachandran, Sokic.

Ma 8. Problem Solving in Calculus. *3 units (3-0-0); first term. Prerequisite: simultaneous registration in Ma 1 a.* A three-hour per week hands-on class for those students in Ma 1 needing extra practice in problem solving in calculus. Instructor: Staff.

Ma 10. Oral Presentation. *3 units (2-0-1); first term. Open for credit to anyone. Freshmen must have instructor's permission to enroll.* In this course, students will receive training and practice in presenting mathematical material before an audience. In particular, students will present material of their own choosing to other members of the class. There may also be elementary lectures from members of the mathematics faculty on topics of their own research interest. Instructor: Rains.

Ma 11. Mathematical Writing. *3 units (0-0-3); third term. Freshmen must have instructor's permission to enroll.* Students will work with the instructor and a mentor to write and revise a self-contained paper dealing with a topic in mathematics. In the first week, an introduction to some matters of style and format will be given in a classroom setting. Some help with typesetting in TeX may be available. Students are encouraged to take advantage of the Hixon Writing Center's facilities. The mentor and the topic are to be selected in consultation with the instructor. It is expected that in most cases the paper will be in the style of a textbook or journal article, at the level of the student's peers (mathematics students at Caltech). *Fulfills the Institute scientific writing requirement.* Not offered on a pass/fail basis. Instructor: Wilson.

Ma 17. How to Solve It. *4 units (2-0-2); first term.* There are many problems in elementary mathematics that require ingenuity for their solution. This is a seminar-type course on problem solving in areas of mathematics where little theoretical knowledge is required. Students will work on problems taken from diverse areas of mathematics; there is no prerequisite and the course is open to freshmen. May be repeated for credit. Graded pass/fail. Instructor: Staff.

Ma 91 a. Homological Algebra. *9 units (3-0-6); first term. Prerequisite: Ma 5 or instructor's permission.* This course will be a first introduction to homological algebra, covering generalities on additive and abelian categories; the category of complexes, and the long exact sequence of cohomology; cones and homotopies; the homotopic category of complexes; projective and injective resolutions, and the derived category; derived functors; double complexes; spectral sequences; and further topics as time permits. Not offered 2010–11.

Ma 92 abc. Senior Thesis. *9 units (0-0-9); first, second, third terms. Prerequisite: To register, the student must obtain permission of the mathematics undergraduate representative, Richard Wilson.* Open only to senior mathematics majors who are qualified to pursue independent reading and research. This research must be supervised by a faculty member. The research must begin in the first term of the senior year and will normally follow up on an earlier SURF or independent reading project. Two short presentations to a thesis committee are required: the first at the end of the first term and the second at the midterm week of the third term. A draft of the written thesis must be completed and distributed to the committee one week before the second presentation. Graded pass/fail in the first and second terms; a letter grade will be given in the third term.

Ma 98. Independent Reading. *3–6 units by arrangement.* Occasionally a reading course will be offered after student consultation with a potential supervisor. Topics, hours, and units by arrangement. Graded pass/fail.

Ma 105. Elliptic Curves. *9 units (3-0-6); first term. Prerequisites: Ma 5, Ma 3, or equivalents.* The ubiquitous elliptic curves will be analyzed from elementary, geometric, and arithmetic points of view. Possible topics are the group structure via the chord-and-tangent method, the Nagel-Lutz procedure for finding division points, Mordell's theorem on the finite generation of rational points, points over finite fields through a special case treated by Gauss, Lenstra's factoring algorithm, integral points. Other topics may include diophantine approximation and complex multiplication. Not offered 2010–11.

Ma 108 abc. Classical Analysis. *9 units (3-0-6); first, second, third terms. Prerequisite: Ma 2 or equivalent, or instructor's permission. May be taken concurrently with Ma 109.* First term: structure of the real numbers, topology of metric spaces, a rigorous approach to differentiation in R^n. Second term: brief introduction to ordinary differential equations; Lebesgue integration and an introduction to Fourier analysis. Third term: the theory of functions of one complex variable. Instructors: van de Bult, Duits, Lee.

Ma 109 abc. Introduction to Geometry and Topology. *9 units (3-0-6); first, second, third terms. Prerequisites: Ma 2 or equivalent, and Ma 108 must be taken previously or concurrently.* First term: aspects of point set topology, and an introduction to geometric and algebraic methods in topology. Second term: the differential geometry of curves and surfaces in two- and three-dimensional Euclidean space. Third term: an introduction to differentiable manifolds. Transversality, differential forms, and further related topics. Instructors: Day, Wu.

Ma 110 abc. Analysis, I. *9 units (3-0-6); first, second, third terms.Prerequisite: Ma 108 or previous exposure to metric space topology, Lebesgue measure.* First term: integration theory and basic real analysis: topological spaces, Hilbert space basics, Fejer's theorem, measure theory, measures as functionals, product measures, L^p-spaces, Baire category, Hahn-Banach theorem, Alaoglu's theorem, Krein-Millman theorem, countably normed spaces, tempered distributions and the Fourier transform. Second term: basic complex analysis: analytic functions, conformal maps and fractional linear transformations, idea of Riemann surfaces, elementary and some special functions, infinite sums and products, entire and meromorphic functions, elliptic functions. Third term: harmonic analysis; operator theory. Harmonic analysis: maximal functions and the Hardy-Littlewood maximal theorem, the maximal and Birkoff ergodic theorems, harmonic and subharmonic functions, theory of H^p-spaces and boundary values of analytic functions. Operator theory: compact operators, trace and determinant on a Hilbert space, orthogonal polynomials, the spectral theorem for bounded operators. If time allows, the theory of commutative Banach algebras. Instructors: Kruger, Rains, Simon.

Ma 111 b. Analysis, II. *9 units (3-0-6); second term. Prerequisite: Ma 110 or instructor's permission.* This course will discuss advanced topics in analysis, which vary from year to year. Topics from previous years include potential theory, bounded analytic functions in the unit disk, probabilistic and combinatorial methods in analysis, operator theory, C*-algebras, functional analysis. Second term: advanced topics in complex analysis chosen from among: elliptical functions, introduction to analytic number theory, Riemannian geometry in complex analysis, complex ODEs, asymptotic methods. Instructor: Simon.

Ma 112 ab. Statistics. *9 units (3-0-6); first, second terms. Prerequisite: Ma 2 a probability and statistics or equivalent.* The first term covers general methods of testing hypotheses and constructing confidence sets, including regression analysis, analysis of variance, and nonparametric methods. The second term covers permutation methods and the bootstrap, point estimation, Bayes methods, and multistage sampling. Not offered 2010–11.

Ma 116 abc. Mathematical Logic and Axiomatic Set Theory. *9 units (3-0-6); first, second, third terms. Prerequisite: Ma 5 or equivalent, or instructor's permission.* Propositional logic, predicate logic, formal proofs, Gödel completeness theorem, the method of resolution, elements of model theory. Computability, undecidability, Gödel incompleteness theorems. Axiomatic set theory, ordinals, transfinite induction and recursion, iterations and fixed points, cardinals, axiom of choice. Not offered 2010–11.

Ma/CS 117 abc. Computability Theory. *9 units (3-0-6); first, second, third terms. Prerequisite: Ma 5 or equivalent, or instructor's permission.* Various approaches to computability theory, e.g., Turing machines, recursive functions, Markov algorithms; proof of their equivalence. Church's thesis. Theory of computable functions and effectively enumerable sets. Decision problems. Undecidable problems: word problems for groups, solvability of Diophantine equations (Hilbert's 10th problem). Relations with mathematical logic and the Gödel incompleteness theorems. Decidable problems, from number theory, algebra, combinatorics, and logic. Complexity of decision procedures. Inherently complex problems of exponential and superexponential difficulty. Feasible (polynomial time) computations. Polynomial deterministic vs. nondeterministic algorithms, NP-complete problems and the P = NP question. Instructor: Kechris.

Ma 118. Topics in Mathematical Logic: Geometrical Paradoxes. *9 units (3-0-6); second term. Prerequisite: Ma 5 or equivalent, or instructor's permission.* This course will provide an introduction to the striking paradoxes that challenge our geometrical intuition. Topics to be discussed include geometrical transformations, especially rigid motions; free groups; amenable groups; group actions; equidecomposability and invariant measures; Tarski's theorem; the role of the axiom of choice; old and new paradoxes, including the Banach-Tarski paradox, the Laczkovich paradox (solving the Tarski circle-squaring problem), and the Dougherty-Foreman paradox (the solution of the Marczewski problem). Not offered 2010–11.

Ma 120 abc. Abstract Algebra. *9 units (3-0-6); first, second, third terms. Prerequisite: Ma 5 or equivalent. Undergraduates who have not taken Ma 5 must have instructor's permission.* Basic theory of groups, rings, modules, and fields, including free groups; Sylow's theorem; solvable and nilpotent groups; factorization in commutative rings; integral extensions; Wedderburn theorems; Jacobson radical; semisimple, projective, and injective modules; tensor products; chain conditions; Galois theory; cyclotomic extensions; separability; transcendental extensions. Instructors: Aschbacher, Mantovan.

Ma 121 abc. Combinatorial Analysis. *9 units (3-0-6); first, second, third terms. Prerequisite: Ma 5.* A survey of modern combinatorial mathematics, starting with an introduction to graph theory and extremal problems. Flows in networks with combinatorial applications. Counting, recursion, and generating functions. Theory of partitions. (0, 1)-matrices. Partially ordered sets. Latin squares, finite geometries, combinatorial designs, and codes. Algebraic graph theory, graph embedding, and coloring. Instructors: Balachandran, van de Bult.

Ma 122 abc. Topics in Group Theory. *9 units (3-0-6); first, second, third terms.* Topics to be decided by instructor. Instructor: Staff.

Ma 123. Classification of Simple Lie Algebras. *9 units (3-0-6); third term. Prerequisite: Ma 5 or equivalent.* This course is an introduction to Lie algebras and the classification of the simple Lie algebras over the complex numbers. This will include Lie's theorem, Engel's theorem, the solvable radical, and the Cartan Killing trace form. The classification of simple Lie algebras proceeds in terms of the associated reflection groups and a classification of them in terms of their Dynkin diagrams. Not offered 2010–11.

EE/Ma 126 ab. Information Theory. *9 units (3-0-6).* For course description, see Electrical Engineering.

EE/Ma/CS 127. Error-Correcting Codes. *9 units (3-0-6).* For course description, see Electrical Engineering.

CS/EE/Ma 129 abc. Information and Complexity. *9 units (3-0-6) first, second terms; (1-4-4) third term.* For course description, see Computer Science.

Ma 130 abc. Algebraic Geometry. *9 units (3-0-6); first, second, third terms. Prerequisite: Ma 120 (or Ma 5 plus additional reading).* Plane curves, rational functions, affine and projective varieties, products, local properties, birational maps, divisors, differentials, intersection numbers, schemes, sheaves, general varieties, vector bundles, coherent sheaves, curves and surfaces. Instructors: Flach, Graber.

Ma 132 c. Topics in Algebraic Geometry. *9 units (3-0-6); third term. Prerequisites: Ma 130 or instructor's permission.* This course will cover advanced topics in algebraic geometry that will vary from year to year. This year, the topic will be deformation theory. Instructor: Graber.

Ma 135 ab. Arithmetic Geometry. *9 units (3-0-6); first, second terms. Prerequisite: Ma 130.* The course deals with aspects of algebraic geometry that have been found useful for number theoretic applications. Topics will be chosen from the following: general cohomology theories (étale cohomology, flat cohomology, motivic cohomology, or p-adic Hodge theory), curves and Abelian varieties over arithmetic schemes, moduli spaces, Diophantine geometry, algebraic cycles. Not offered 2010–11.

Ma/ACM 142. Ordinary and Partial Differential Equations. *9 units (3-0-6); third term. Prerequisite: Ma 108; Ma 109 is desirable.* The mathematical theory of ordinary and partial differential equations, including a discussion of elliptic regularity, maximal principles, solubility of equations. The method of characteristics. Instructor: Duits.

Ma/ACM 144 ab. Probability. *9 units (3-0-6); first, second terms.* Overview of measure theory. Random walks and the Strong law of large numbers via the theory of martingales and Markov chains. Characteristic functions and the central limit theorem. Poisson process and Brownian motion. Topics in statistics. Instructor: Staff.

Ma 145 abc. Introduction to Unitary Group Representations. *9 units (3-0-6); first, second, third terms.* The study of representations of a group by unitary operators on a Hilbert space, including finite and compact groups, and, to the extent that time allows, other groups. First term: general representation theory of finite groups. Frobenius's theory of representations of semidirect products. The Young tableaux and the representations of symmetric groups. Second term: the Peter-Weyl theorem. The classical compact groups and their representation theory. Weyl character formula. Third term: Quantum Groups. Not offered 2010–11.

Ma 147 abc. Dynamical Systems. *9 units (3-0-6); first, second, third terms. Prerequisites: Ma 108, Ma 109, or equivalent.* First term: real dynamics and ergodic theory. Second term: Hamiltonian dynamics. Third term: complex dynamics. Instructor: Makarov. Third term not offered 2010–11.

Ma 148 c. Topics in Mathematical Physics: Hamiltonian Dynamics. *9 units (3-0-6); third term.* This course covers a range of topics in mathematical physics. The content will vary from year to year. Topics covered will include some of the following: Lagrangian and Hamiltonian formalism of classical mechanics; mathematical aspects of quantum mechanics: Schroedinger equation, spectral theory of unbounded operators, representation theoretic aspects; partial differential equations of mathematical physics (wave, heat, Maxwell, etc.); rigorous results in classical and/or quantum statistical mechanics; mathematical aspects of quantum field theory; general relativity for mathematicians. Third term: mathematics of quantum mechanics and quantum field theories. Instructor: Marcolli.

Ma 151 abc. Algebraic and Differential Topology. *9 units (3-0-6); first, second, third terms. Prerequisite: Ma 108 ab or equivalent.* A basic graduate core course. Fundamental groups and covering spaces, homology and calculation of homology groups, exact sequences. Fibrations, higher homotopy groups, and exact sequences of fibrations. Bundles, Eilenberg-Maclane spaces, classifying spaces. Structure of differentiable manifolds, transversality, degree theory, De Rham cohomology, spectral sequences. Instructors: Ni, Calegari.

Ma 157 a. Riemannian Geometry. *9 units (3-0-6); first term. Prerequisite: Ma 151 or equivalent, or instructor's permission.* Part a: basic Riemannian geometry: geometry of Riemannian manifolds, connections, curvature, Bianchi identities, completeness, geodesics, exponential map, Gauss's lemma, Jacobi fields, Lie groups, principal bundles, and characteristic classes. Part b (not offered 2010–11): basic topics may vary from year to year and may include elements of Morse theory and the calculus of variations, locally symmetric spaces, special geometry, comparison theorems, relation between curvature and topology, metric functionals and flows, geometry in low dimensions. Instructor: Wilton.

Ma 160 abc. Number Theory. *9 units (3-0-6); first, second, third terms. Prerequisite: Ma 5.* In this course, the basic structures and results of algebraic number theory will be systematically introduced. Topics covered will include the theory of ideals/divisors in Dedekind domains, Dirichlet unit theorem and the class group, p-adic fields, ramification, Abelian extensions of local and global fields. Instructors: Flach, Jorza.

Ma 162. Topics in Number Theory. *9 units (3-0-6); third term. Prerequisite: Ma 160.* The course will discuss in detail some advanced topics in number theory, selected from the following: Galois representations, elliptic curves, modular forms, L-functions, special values, automorphic representations, p-adic theories, theta functions, regulators. Instructor: Ramakrishnan.

Note: The courses labeled Ma 191, Ma 192, etc., are topics courses. Different courses are offered each year, reflecting the interests of faculty, visiting faculty, and students. Those offered in the fall term have an "a" designation, and "b" and "c" denote winter and spring. None of these courses is a prerequisite for any other.

Ma 191 a. Automorphism Groups of Free Groups. *9 units (3-0-6); first term.* This course will discuss combinatorial and geometric approaches to understanding automorphism groups of free groups. Topics will include Nielsen reduction, Whitehead's theorem, and Culler-Vogtmann Outer space. Instructor: M. Day.

Ma 191 b. Structural Ramsey Theory and Topological Dynamics. *9 units (3-0-6); second term.* This course will cover the basics of Ramsey theory and its relations to topological dynamics. We will start with the classical Ramsey Theorem and present some of its applications. We will then discuss extensions of the Ramsey Theorem to many other classes of finite structures such as vector spaces over finite fields, linearly ordered graphs, and ordered metric spaces. The closely related ordering property for a class of finite structures will be also introduced. It has been recently discovered that these combinatorial properties of finite structures are closely related to the study of minimal flows in topological dynamics, and we will also discuss these intriguing connections. The course should be of interest to students interested in combinatorics, logic, or dynamical systems. No particular prerequisites are required and the treatment will be as elementary as possible, so that it can be also taken by undergraduates. Instructor: Sokic.

Ma 191 c. Non-positively Curved Cube Complexes. *9 units (3-0-6); third term.* Non-positively curved cube complexes are a remarkable class of topological spaces, in which geometric properties can be rephrased combinatorially. In this class, we will cover the theory of these complexes and their applications to topology and group theory. Topics will include CAT(0) metric spaces and groups; Wise's example of a non-Hopfian CAT(0) group; Sageev's cubulation criterion; right-angled Artin groups and Salvetti complexes and Haglund and Wise's special cube complexes. Instructor: Wilton.

Ma 192 a. Topics in Conformal Field Theory. *9 units (3-0-6); first term. Prerequisite: Ma 108 or instructor's permission.* The course will discuss a mathematical introduction to conformal field theory. Topics will cover Fock space, Feynman calculus, Gaussian free field, Feigin-Fuchs-Miura transform, stress-energy tensor, Ward identities, chiral vertex fields, and applications in representation theory. The course will present relations between conformal field theory and Schramm-Loewner evolutions in the chordal, radial, and dipolar case, respectively. Not offered 2010–11.

Ma 192 b. Topics in Riemann-Hilbert Problems and Asymptotic Analysis. *9 units (3-0-6); second term.* The goal of the course is to illustrate how the method of steepest descent for Riemann-Hilbert problems can be used to obtain asymptotic results for orthogonal polynomials and for Painlevé equations. The main focus will be on orthogonal polynomials on the real line. Instructor: Lee.

Ma 192 c. Hopf Algebras and Renormalization. *9 units (3-0-6); third term.* The purpose of this course is to understand the Connes Kreimer renormalization process of QFTs, on both a tree and diagram level. The course will cover the Hopf algebras of trees and diagrams, Birkhoff decomposition, Rota-Baxter algebras, and other topics as directed by students. Instructor: Agarwala.

Ma 193 a. Krein-de Branges Spaces and Classical Problems of Linear Complex Analysis. *9 units (3-0-6); first term.* Krein-De Branges spaces of entire functions, canonical systems and Krein-De Branges solution of the inverse spectral problem, related questions of linear complex analysis (polynomial and exponential density and moment problems, completeness and minimality, gap theorems). Not offered 2010–11.

SS/Ma 214. Mathematical Finance. *9 units (3-0-6).* For course description, see Social Science.

Ma 290. Reading. *Hours and units by arrangement.* Occasionally, advanced work is given through a reading course under the direction of an instructor.

Ma 390. Research. *Units by arrangement.*

See also the list of courses in Applied and Computational Mathematics.

Additional advanced courses in the field of mechanical engineering may be found listed in other engineering options such as aerospace engineering, applied mechanics, applied physics, control and dynamical systems, and materials science.

ME 18 ab. Thermodynamics. *9 units (3-0-6); second, third terms. Prerequisites: Ph 1 and Ph 2 (may be taken concurrently).* An introduction to classical thermodynamics with engineering applications. First term includes the first and second laws; closed and open systems; properties of a pure substance; availability and irreversibility; generalized thermodynamic relations. Second term emphasizes applications: gas and vapor power cycles; propulsion; mixtures; combustion and thermochemistry; chemical equilibrium. Instructors: Colonius.

ME 19 ab. Fluid Mechanics. *9 units (3-0-6); first, second terms. Prerequisites: Ma 2, Ph 1 abc.* Properties of fluids, basic equations of fluid mechanics, theorems of energy, linear and angular momentum. Euler's equations, inviscid potential flow, surface waves, airfoil theory. Navier-Stokes equations, vorticity and vorticity transport. Flow of real fluids, similarity parameters, flow in ducts. Boundary layer theory for laminar and turbulent flow, transition to turbulence. Drag, lift, and propulsion. Instructors: Hunt, staff.

ME 20. Heat Transfer. *9 units (3-0-6); third term. Prerequisites: ME 18 ab, ME 19 ab.* An introduction to heat transfer. Steady-state and transient conduction, including numerical solutions. Forced and natural convective-heat transfer. Heat exchangers. Radiative heat transfer and solar energy. Taught concurrently with ME 119 a. Not offered 2010–11.

ME 35 abc. Statics and Dynamics. *9 units (3-0-6); first, second, third terms. Prerequisites: Ma 1 abc, Ph 1 abc.* Introduction to statics and dynamics of rigid and deformable bodies. Equilibrium of force systems, principle of virtual work, distributed force systems, friction, static analysis of rigid and deformable structures, kinematics, particle dynamics, rigid-body dynamics, dynamics of deformable systems, and vibrating systems. Instructors: Ravichandran, staff.

ME 65. Mechanics of Materials. *9 units (3-0-6); first term. Prerequisites: ME 35 abc, Ma 2 ab.* Introduction to continuum mechanics, principles of elasticity, plane stress, plane strain, axisymmetric problems, stress concentrations, thin films, fracture mechanics, variational principles, frame structures, finite element methods, composites, and plasticity. Taught concurrently with Ae/AM/CE/ME 102. Instructor: Bhattacharya.

ME 66. Vibration. *9 units (3-0-6); second term. Prerequisites: ME 35 abc, Ma 2 ab.* Introduction to vibration and wave propagation in continuous and discrete multi-degree-of-freedom systems. Strings, mass-spring systems, mechanical devices, elastic continua. Equations of motion, Lagrange's equations, Hamilton's principle, and time-integration schemes. Taught concurrently with AM/CE 151 a. Instructor: Heaton.

ME 71. Introduction to Engineering Design. *9 units (3-5-1); third term. Prerequisite: ME 35 ab recommended. Enrollment is limited and will be based on responses to a questionnaire available in the Registrar's Office during registration. Not offered on a pass/fail basis.* Introduction to mechanical engineering design, fabrication, and visual communication. Concepts are taught through a series of short design projects and design competitions emphasizing physical concepts. Many class projects will involve substantial use of the shop facilities, and construction of working prototypes. Instructor: Staff.

ME 72 ab. Engineering Design Laboratory. *9 units (3-4-2), first term; (1-8-0), second term. Prerequisites: ME 35 abc, ME 71, Me 18 ab, CS 1 or equivalent, and instructor's permission. Enrollment is limited.* A project-based course in which teams of students design, fabricate, analyze, test, and operate an electromechanical device to compete against devices designed by other student teams. The class lectures and the projects stress the integration of mechanical design, sensing, engineering analysis, and computation to solve problems in engineering system design. The laboratory units of ME 72 can be used to fulfill a portion of the laboratory requirement for the ME or EAS option. Not offered on a pass/fail basis. Instructor: Staff.

CS/EE/ME 75 abc. Introduction to Multidisciplinary Systems Engineering. *3 units (2-0-1) first term; 3–6 units second term; 12 units (2-9-1) or 18 units (2-15-1) third term.* For course description, see Computer Science.

ME 90 abc. Senior Thesis, Experimental. *9 units; (0-0-9) first term; (0-9-0) second, third terms. Prerequisites: senior status; instructor's permission.* Experimental research supervised by an engineering faculty member. The topic selection is determined by the adviser and the student and is subject to approval by the Mechanical Engineering Undergraduate Committee. First and second terms: midterm progress report and oral presentation during finals week. Third term: completion of thesis and final presentation. The second and third terms may be used to fulfill laboratory credit for EAS. Not offered on a pass/fail basis. Instructor: Lapusta.

ME 91 abc. Senior Thesis, Analytical. *9 units (0-0-9); first, second, third terms. Prerequisites: senior status; instructor's permission.* Undergraduate research supervised by an engineering faculty member. The topic selection is determined by the adviser and the student and is subject to approval by the Mechanical Engineering Undergraduate Committee. First and second terms: midterm progress report and oral presentation during finals week. Third term: completion of thesis and final presentation. Not offered on a pass/fail basis. Instructor: Lapusta.

ME 96. Mechanical Engineering Laboratory. *9 units (0-9-0); third term. Prerequisites: ME 18 ab, ME 19 ab, ME 35 ab.* A laboratory course with experiments drawn from diverse areas of mechanical engineering, including heat transfer, control, fluid mechanics, solid mechanics, atomic force microscopy, materials, combustion, turbomachinery, and dynamics. Instructor: Staff.

ME 100. Advanced Work in Mechanical Engineering. The faculty in mechanical engineering will arrange special courses on problems to meet the needs of qualified undergraduate students. Graded pass/fail for research and reading. A written report is required for each term.

Ae/APh/CE/ME 101 abc. Fluid Mechanics. *9 units (3-0-6).* For course description, see Aerospace.

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

E/ME 103. Management of Technology. *9 units (3-0-6).* For course description, see Engineering.

E/ME 105. Product Design for the Developing World. *9 units (3-0-6).* For course description, see Engineering.

EST/EE/ME 109 ab. Energy. *9 units(3-0-6.)* For course description, see Energy Science and Technology.

ME 110. Special Laboratory Work in Mechanical Engineering. *3–9 units per term; maximum two terms.* Special laboratory work or experimental research projects may be arranged by members of the faculty to meet the needs of individual students as appropriate. A written report is required for each term of work. Instructor: Staff.

ME 115 ab. Introduction to Kinematics and Robotics. *9 units (3-0-6); second, third terms. Prerequisites: Ma 2, ACM 95/100 ab recommended.* Introduction to the study of planar, rotational, and spatial motions with applications to robotics, computers, computer graphics, and mechanics. Topics in kinematic analysis will include screw theory, rotational representations, matrix groups, and Lie algebras. Applications include robot kinematics, mobility in mechanisms, and kinematics of open and closed chain mechanisms. Additional topics in robotics include path planning for robot manipulators, dynamics and control, and assembly. Course work will include laboratory demonstrations using simple robot manipulators. Instructor: Staff.

ME 118. Thermodynamics. *9 units (3-0-6); first term. Prerequisites: ME 18 ab, ME 19 ab.* Fundamentals of classical and statistical thermodynamics. Basic postulates, thermodynamic potentials, chemical and phase equilibrium, phase transitions, and thermodynamic properties of solids, liquids, and gases. Taught concurrently with ChE/Ch 165. Instructor: Staff.

ME 119 ab. Heat and Mass Transfer. *9 units (3-0-6); second, third terms. Prerequisites: ME 18 ab, ME 19 ab, ACM 95/100 (may be taken concurrently).* Transport properties, conservation equations, conduction heat transfer, convective heat and mass transport in laminar and turbulent flows, phase change processes, thermal radiation. Instructor: Blanquart.

Ae/ME 120 ab. Combustion Fundamentals. *9 units (3-0-6).* For course description, see Aerospace.

ME 131. Advanced Robotics: Manipulation and Sensing. *9 units (3-6-0); third term. Prerequisite: ME 115 ab.* The course focuses on current topics in robotics research in the area of robotic manipulation and sensing. Past topics have included advanced manipulator kinematics, grasping and dextrous manipulation using multifingered hands, and advanced obstacle avoidance and motion planning algorithms. The lectures will be divided between a review of the appropriate analytical techniques and a survey of the current research literature. Course work will focus on an independent research project chosen by the student. Not offered 2010–11.

ME/CS 132 ab. Advanced Robotics: Navigation and Vision. *9 units (3-6-0); second, third terms. Prerequisite: ME 115 ab.* The course focuses on current topics in robotics research in the area of autonomous navigation and vision. Topics will include mobile robots, multilegged walking machines, use of vision in navigation systems. The lectures will be divided between a review of the appropriate analytical techniques and a survey of the current research literature. Course work will focus on an independent research project chosen by the student. Instructor: Staff.

ME 150 abc. Mechanical Engineering Seminar. *1 unit; each term.* All candidates for the M.S. degree in applied mechanics and mechanical engineering are required to attend any graduate seminar in any division each week of each term. Graded pass/fail. Instructor: Lapusta.

Ae/Ge/ME 160 ab. Continuum Mechanics of Fluids and Solids. *9 units (3-0-6).* For course description, see Aerospace.

MS/ME 161. Imperfections in Crystals. *9 units (3-0-6).* For course description, see Materials Science.

MS/ME 162. Mechanical Behavior of Materials. *9 units (3-0-6).* For course description, see Materials Science.

AM/ME 165 ab. Elasticity. *9 units (3-0-6).* For course description, see Applied Mechanics.

ME 170. Introduction to Mechanical Prototyping. *4 units (0-0-4); first, third, summer terms.* Enrollment is limited and is based on responses to a questionnaire available in the Registrar's Office during registration. Introduction to the technologies and practices needed to fabricate mechanical prototypes. Students will be introduced to both manual and computer-aided machining techniques, as well as computer-controlled prototyping technologies, such as three-dimensional printing and water jet cutting. Students will receive safety training, instruction on the theories underlying different machining methods, and hands-on demonstrations of machining and mechanical assembly methods. Several prototypes will be constructed using the various technologies available in the mechanical engineering machine shop. Experience with computer-aided drafting tools is helpful but not essential. Instructor: Staff.

EST/MS/ME 199. Special Topics in Energy Science and Technology. *Units to be arranged.* For course description, see Energy Science and Technology.

ME 200. Advanced Work in Mechanical Engineering. The faculty in mechanical engineering will arrange special courses on problems to meet the needs of graduate students. Graded pass/fail; a written report is required for each term of work.

ME 202 abc. Engineering Two-Phase Flows. *9 units (3-0-6). Prerequisites: ACM 95/100 abc, Ae/APh/CE/ME 101 abc, or equivalents.* Selected topics in engineering two-phase flows with emphasis on practical problems in modern hydro-systems. Fundamental fluid mechanics and heat, mass, and energy transport in multiphase flows. Liquid/vapor/gas (LVG) flows, nucleation, bubble dynamics, cavitating and boiling flows, models of LVG flows; instabilities, dynamics, and wave propagation; fluid/structure interactions. Discussion of two-phase flow problems in conventional, nuclear, and geothermal power plants, marine hydrofoils, and other hydraulic systems. Not offered 2010–11.

Ae/AM/MS/ME 213. Mechanics and Materials Aspects of Fracture. *9 units (3-0-6).* For course description, see Aerospace.

Ae/AM/CE/ME 214 abc. Computational Solid Mechanics. *9 units (3-0-6).* For course description, see Aerospace.

Ae/AM/ME 215. Dynamic Behavior of Materials. *9 units (3-0-6).* For course description, see Aerospace.

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

Ae/AM/ME 225. Special Topics in Solid Mechanics. *Units to be arranged.* For course description, see Aerospace.

Ae/ACM/ME 232 abc. Computational Fluid Dynamics. *9 units (3-0-6).* For course description, see Aerospace.

ME/MS 260 abc. Micromechanics. *12 units (3-0-9). Prerequisites: ACM 95/100 or equivalent, and Ae/AM/CE/ME 102 abc or Ae 160 abc or* *instructor's permission.* The course gives a broad overview of micromechanics, emphasizing the microstructure of materials, its connection to molecular structure, and its consequences on macroscopic properties. Topics include phase transformations in crystalline solids, including martensitic, ferroelectric, and diffusional phase transformations, twinning and domain patterns, active materials; effective properties of composites and polycrystals, linear and nonlinear homogenization; defects, including dislocations, surface steps, and domain walls; thin films, asymptotic methods, morphological instabilities, self-organization; selected applications to microactuation, thin-film processing, composite materials, mechanical properties, and materials design. Open to undergraduates with instructor's permission. Not offered 2010–11.

Ae/Ge/ME 266 ab. Dynamic Fracture and Frictional Faulting. *9 units (3-0-6).* For course description, see Aerospace.

ME 300. Research in Mechanical Engineering. *Hours and units by arrangement.* Research in the field of mechanical engineering. By arrangement with members of the faculty, properly qualified graduate students are directed in research.

MUSIC

Mu 10. Selected Topics in Music; *offered by announcement. Units to be determined by arrangement with instructor.* Instructors: Staff, visiting lecturers.

Mu 21. Understanding Music. *9 units (3-0-6); first term.* The Listening Experience I. How to listen to and what to listen for in classical and other musical expressions. Listening, analysis, and discussion of musical forms, genres, and styles. Course is intended for musicians as well as nonmusicians and is strongly recommended as an introduction to other music courses. Instructor: Neenan.

Mu 24. Introduction to Opera. *9 units (3-0-6); third term.* Opera exploded onto the cultural scene around the year 1600 and quickly became the most popular, expensive, and lavish spectacle in all of Europe. The course will trace the history of the genre examining masterpieces by Monteverdi, Handel, Mozart, Rossini, Verdi, Wagner, Strauss, Berg, and Britten, and will sample a host of newer works, including *Einstein on the Beach*, *The Death of Klinghoffer*, and *The Ghosts of Versailles*. Not offered 2010–11.

Mu 25. History of Chamber Music. *9 units (3-0-6); third term.* To be coordinated with Caltech's spring chamber music performances; enrollment limited to students preparing performances of chamber music during the term. The course will survey the history of chamber music and will offer more in-depth exploration of works in preparation for performance. Instructor: Neenan.

Mu 26. Jazz History. *9 units (3-0-6); second term.* This course will examine the history of jazz in America from its roots in the unique confluence of racial and ethnic groups in New Orleans around 1900 to the present. The lives and music of major figures such as Robert Johnson, Jelly Roll Morton, Louis Armstrong, Benny Goodman, Duke Ellington, Count Basie, Charlie Parker, Dizzy Gillespie, Thelonius Monk, Miles Davis and others will be explored. Instructor: Neenan.

Mu 27. Fundamentals of Music Theory and Elementary Ear Training. *9 units (3-0-6); first term.* Basic vocabulary and concepts of music theory (rhythm and pitch notation, intervals, scales, function of key signatures, etc.); development of aural perception via elementary rhythmic and melodic dictation, and sight-singing exercises. Instructor: Neenan.

Mu 28. Harmony I. *9 units (3-0-6), second term. Prerequisite: Mu 27 or entrance exam.* Study of tonal harmony and intermediate music theory; techniques of chord progression, modulation, and melody writing according to common practice; ear training, continued. Not offered 2010–11.

Mu 29. Harmony II. *9 units (3-0-6), third term. Prerequisite: Mu 28 or entrance exam.* More advanced concepts of music theory, including chromatic harmony, and 20th-century procedures relating to selected popular music styles; ear training, continued. Not offered 2010–11.

Mu 122. Life and Music of Mozart. *9 units (3-0-6); second term.* This course will explore Mozart's music within the context of his life and times, including the early works composed as a child prodigy and touring artist; the first masterpieces he composed, and finally the masterworks written during his meteoric rise and his equally amazing fall from grace. Not offered 2010–11.

Mu 123. Life and Music of Beethoven. *9 units (3-0-6); third term.* The course will examine the exuberant works of Beethoven's youth, the series of grand, heroic masterpieces of the early 1800s, and the puzzling and mysterious works of his final decade. Instructor: Neenan.

Mu 137. History I: Music History to 1750. *9 units (3-0-6); first term.* The course traces the history of music from ancient Greece to the time of Bach and Handel. A survey of the contributions by composers such as Machaut, Josquin, and Palestrina will lead to a more in-depth look at the music of Monteverdi, Purcell, Corelli, Vivaldi, and the two most important composers of the high baroque, Bach and Handel. Instructor: Neenan. Given in alternate years; not offered 2010–11.

Mu 138. History II: Music History from 1750 to 1850. *9 units (3-0-6); second term.* Music composed between 1750 and 1850 is among the most popular concert music of today and the most recorded music in the classical tradition. This course will focus on developments in European music during this critical period. An in-depth look at the music of Haydn, Mozart, and Beethoven along with the cultural and societal influences that shaped their lives will be the primary focus. Music of composers immediately preceding and following them (the Bach sons, Schubert, Chopin, and others) will also be surveyed. Instructor: Neenan. Given in alternate years; not offered 2010–11.

Mu 139. History III: Music History from 1850 to the Present. *9 units (3-0-6); third term.* From the end of the 19th century to the present day, classical music has undergone the fastest and most radical changes in its history. The course explores these changes, tracing the development of various musical styles, compositional methods, and music technologies while examining acknowledged masterpieces from throughout the period. Instructor: Neenan. Given in alternate years; not offered 2010–11.

Mu 140. The Great Orchestras: Their History, Repertoire, and Conductors. *9 units (3-0-6); second term.* This survey course will trace the symphony orchestra from its generally acknowledged beginnings with the Leipzig Gewandhaus Orchestra under Felix Mendelssohn to the present day. Special emphasis will be given to the great orchestras of the late nineteenth and twentieth centuries, their conductors, and the core orchestral repertoire. Making use of historic audio and video recordings from the twentieth century, along with more recent documentary recordings, students will be exposed to the cultural history of modern Europe and America through the medium of classical music. Instructor: Neenan.

PERFORMANCE AND ACTIVITIES

Courses under this heading cover the instructional content of a range of extracurricular activities and work in the fine arts and elsewhere. These courses will appear on the student's transcript, and will be graded pass/fail only. The units count toward the total unit requirement for graduation, but they do not count toward the 108-unit requirement in humanities and social sciences.

PA 15 abc. Student Publications. *3 units (1-0-2); first, second, third terms.* The elementary principles of newspaper writing and editing, with special attention to student publications at the Institute. Instructor: Staff.

PA 16 abc. Cooking Basics. *3 units (0-3-0); first, second, third terms.* The class will survey different cooking styles, techniques, and cuisines from around the world. Topics covered may include knives and tools; tastes and flavors; sauces and reductions; legumes, grains, and beans; meat; dessert. The emphasis will be on presentation and creativity. Instructor: Mannion.

PA 20 abc. Debate. *3 units (1-0-2); first, second, third terms.* Study and discussion of the annual intercollegiate debate topic. Instructor: Staff.

PA 30 abc. Guitar. *3 units (0-3-0); first, second, third terms.* Offered on three levels: beginning (no previous experience required), intermediate, and advanced. Instruction emphasizes a strong classical technique, including an exploration of various styles of guitar—classical, flamenco, folk, and popular. Instructor: Elgart.

PA 31 abc. Chamber Music. *3 units (0-3-0); first, second, third terms.* Study and performance of music for instrumental ensembles of two to eight members, and for piano four-hands. Literature ranges from the 16th to 21st centuries. Open to students who play string, woodwind, brass instruments, guitar, or piano. After auditioning, pianists will be placed in sections by the instructors. Section 1: Mixed ensembles. Instructor: D. Bing. Section 2: Piano four-hands. Instructor: Ward. Section 3: Guitar ensemble. Instructor: Elgart.

PA 32 abc. Symphony Orchestra. *3 units (0-3-0); first, second, third terms.* Study and performance of music written for full symphony orchestra and chamber orchestra. The orchestra performs both the standard symphonic repertoire and contemporary music. Two and a half hours of rehearsal per week. Instructor: Gross.

PA 33 abc. Concert Band. *3 units (0-3-0); first, second, third terms.* Study and performance of music written for the classical wind ensemble and concert band. Emphasis is placed on the traditional literature, but the study of contemporary music is an important part of the curriculum. Instructor: W. Bing.

PA 34 abc. Jazz Band. *3 units (0-3-0); first, second, third terms.* Study and performance of all styles of big-band jazz, from Duke Ellington to Maria Schneider. The study of jazz improvisation is also encouraged. Instructor: W. Bing.

PA 35 abc. Women's Glee Club. *3 units (0-3-0); first, second, third terms.* Preparation and performance of women's and SATB choral repertoire spanning a range of historical periods and musical styles. Includes collaborative performances with the Men's Glee Club and occasionally with orchestra. No previous experience required. Three hours a week. Instructor: Sulahian.

PA 36 abc. Men's Glee Club. *3 units (0-3-0); first, second, third terms.* Preparation and performance of men's and SATB choral repertoire, spanning a range of historical periods and musical styles. Includes collaborative performances with the Women's Glee Club and occasionally with orchestra. No previous experience required. Three hours per week. Instructor: Sulahian.

PA 37 abc. Chamber Singers. *3 units (0-3-0); first, second, third terms.* Advanced study and performance of SATB choral music. Emphasis is placed on more difficult choral repertoire, both a capella and accompanied. Includes performances with the Glee Clubs as well as at other on-campus events. Audition required. Participation in Glee Clubs required. Instructor: Sulahian.

PA 40 abc. Theater Arts. *3 units (2-0-1); first, second, third terms.* Instruction in all phases of theatrical production, culminating in multiple performances for the public. A hands-on, practical approach includes workshops in stage combat, costume construction, scenic arts, occasional informal encounters with professional actors, designers, and directors. Understanding of dramatic structure, respect for production values, and problem solving are stressed. Material of academic value is drawn from 3,000 years of worldwide dramatic literature. Instructor: Brophy.

PA 61 abc. Silkscreen and Silk Painting. *3 units (0-3-0); first, second, third terms.* Instruction in silkscreening techniques, primarily for T-shirts. Progressive development of silk painting skills for fine art. Instructor: Barry.

PA 62 abc. Drawing and Painting. *3 units (0-3-0); first, second, third terms.* Instruction in techniques of painting in acrylics and watercolor and life drawing of models. Emphasis on student-chosen subject with a large reference library. Instructor: Barry.

PA 63 abc. Ceramics. *3 units (0-3-0); first, second, third terms.* Instruction in the techniques of creating ceramics, including the slab roller and potter's wheel, and glazing methods. Instructor: Freed.

PA 70 abc. Student-Taught Courses. *3 units (2-0-1); first, second, third terms.* A variety of subjects each term, taught by undergraduate students. Different subjects will fall under different section numbers. The courses offered each term will be decided based on student interest and a selection process by the Office of Student Affairs. More information at http://www.deans.caltech.edu/studenttaughtcourses.htm.

PA 80 abc. Pilot Training. *3 units (3-0-0); first, second, third terms*. A course designed for students interested in aviation who are considering a pilot's license. It will introduce the knowledge aspects of flying and prepare for the required FAA knowledge test. First term: private pilot topics. Second term: instrument flying. Third term: advanced topics (commercial flying, high-altitude flying, advanced systems, advanced weather, etc.). Instructors: Werntz, Areeda.

PHILOSOPHY

Hum/Pl 8. Right and Wrong. *9 units (3-0-6)*. For course description, see Humanities.

Hum/Pl 9. Knowledge and Reality. *9 units (3-0-6).* For course description, see Humanities.

Pl 90 ab. Senior Thesis. *9 units (1-0-8).* Required of students taking the philosophy option. To be taken in any two consecutive terms of the senior year. Students will research and write a thesis of 10,000–12,000 words on a philosophical topic to be determined in consultation with their thesis adviser. Limited to students taking the philosophy option. Instructor: Staff.

Pl 98. Reading in Philosophy. *9 units (1-0-8). Prerequisite: instructor's permission.* An individual program of directed reading in philosophy, in areas not covered by regular courses. Instructor: Staff.

Pl 102. Selected Topics in Philosophy. *9 units (3-0-6); offered by announcement. Prerequisite: Hum/Pl 8 or Hum/Pl 9 or instructor's permission.*

Pl 103. Medieval Philosophy. *9 units (3-0-6); third term.* This course examines the philosophy of Western Europe from the decline of pagan culture to the Renaissance, roughly 400–1400 C.E. Material covered will vary, but will likely include a thorough introduction to Late Greek neo-Platonic philosophy as background to reading figures such as Augustine, Boethius, Avicenna, Abailard, Averroes, Maimonides, Anselm, Albert the Great, Aquinas, Olivi, Scotus, and Ockham. Not offered 2010–11.

HPS/Pl 120. Introduction to Philosophy of Science. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/Pl 121. Causation and Explanation. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/Pl 122. Confirmation and Induction. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/Pl 124. Philosophy of Space and Time. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/Pl 125. Philosophical Issues in Quantum Physics. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/Pl 128. Philosophy of Mathematics. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/Pl 129. Introduction to Philosophy of Biology. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/Pl 130. Philosophy and Biology. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/Pl 132. Introduction to Philosophy of Mind and Psychology. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/Pl 133. Philosophy and Neuroscience. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/Pl 134. Current Issues in Philosophical Psychology. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/Pl 136. Ethics in Research. *4 units (2-0-2) or 9 units (2-0-7).* For course description, see History and Philosophy of Science.

HPS/Pl 137. Experimental Philosophy. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/Pl 138. Human Nature and Society. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

Pl 150. 17th-Century Philosophy: Bacon to Leibniz. *9 units (3-0-6); first, third terms.* The course will examine the work of several prominent philosophers active during the so-called Century of Genius. Although we will focus on the arguments each author brings to bear in support of his or her philosophical position, historical background will be introduced to provide scientific, religious, and political context. The topics will include the limits of human knowledge, the existence and nature of mind, matter, and God, and the relationship between science and philosophy. Philosophers discussed are selected from Bacon, Mersenne, Descartes, Gassendi, Hobbes, Digby, Spinoza, Malebranche, Arnauld, More, Cudworth, Locke, Newton, and Leibniz. Instructors: Manning, Stan.

Pl 151. 18th-Century Philosophy: Locke to Kant. *9 units (3-0-6); second term.*The course will examine the work of several prominent philosophers active during the so-called Age of Enlightenment. Although we will focus on the arguments each author brings to bear in support of his or her philosophical position, historical background will be introduced to provide scientific, religious, and political context. The topics will include ideas and perception, belief and knowledge, passion and reason, matter and mind, causation and free will, and the relationship between science and philosophy. Philosophers discussed are selected from Locke, Huygens, Leibniz, Newton, Wolff, Berkeley, Rousseau, Hume, Reid, and Kant. Instructor: Manning.

Pl/HPS 157. Leibniz vs. Newton: Philosophers at War. *9 units (3-0-6).*This course takes up a fascinating exchange between Leibniz and Newton, two towering figures at the dawn of modern physical science. It centers on the correspondence between Leibniz and Newton's disciple Samuel Clarke. Their letters (1714–1716) address foundational issues of 17th century dynamics: the existence of space and time; the architecture of matter; God and his agency in the world; miracles and laws of nature; free will and divine choice. A detailed overview of the scientific, philosophical, and religious background to the debate will serve to introduce the debate. Not offered 2010–11.

HPS/Pl 169. Selected Topics in Philosophy of Science. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/H/Pl 173. History of Chemistry. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

Pl/HPS 183. Bioethics. *9 units (3-0-6); third term.* A survey of issues in bioethics. Topics may include reproduction and cloning, stem-cell research, organ transplantation and sale, informed consent, killing vs. letting die, cure vs. enhancement, and research ethics. Instructor: Cowie.

Pl/HPS 184. Science, Ethics, and Public Policy. *9 units (3-0-6); offered by announcement.* This course discusses some moral and social issues concerning research in the sciences (chiefly, biomedicine, with special attention to stem-cell research.) We will begin by discussing attempts to find a framework within which the issues can be addressed, and then we will discuss some specific topics. In most cases we will not so much seek answers to moral questions as attempt to identify helpful questions, clarify the issues involved, and analyze the moral status of the protagonists. We will also pay special attention to issues of public policy, and ask how scientific research should be organized and funded in a democracy. Not offered 2010–11.

Pl 185. Moral Philosophy. *9 units (3-0-6); third term.* A survey of topics in moral philosophy. The emphasis will be on metaethical issues, although some normative questions may be addressed. Metaethical topics that may be covered include the fact/value distinction; the nature of right and wrong (consequentialism, deontological theories, rights-based ethical theories, virtue ethics); the status of moral judgments (cognitivism vs. noncognitivism, realism vs. irrealism); morality and psychology; moral relativism; moral skepticism; morality and self-interest; the nature of justice. The implications of these theories for various practical moral problems may also be considered. Not offered 2010–11.

Pl 186. Political Philosophy. *9 units (3-0-6); offered by announcement.* This course will address one or more issues in contemporary political theory and/or the history of political thought. Topics may include the nature of democracy; liberalism; distributive justice; human rights; the moral and legal regulation of warfare; the status of positive law; social choice theory; the relations between the market and the state. The work of figures such as Plato, Aristotle, Locke, Hobbes, Mill, Machiavelli, and Rawls will be discussed. Not offered 2010–11.

Pl 187. Natural Justice. *9 units (3-0-6); third term.* This course examines the unorthodox view that morality is a natural phenomenon—the product of a combination of biological and cultural evolution. It reviews and criticizes the traditional arguments used to deny both moral natu-ralism and moral relativism, notably the Naturalistic Fallacy. It assesses the success of the approach advocated by evolutionary biologists and psychologists. It examines the evidence from laboratory experiments on fairness and justice. Finally, it attempts to synthesize all these strands using the theory of games as a unifying framework. Not offered 2010–11.

HPS/Pl 188. The Evolution of Cognition. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

PHYSICAL EDUCATION

PE 1 abc. Student Designed Fitness. *3 units. May only be used for 3 units of the 9-unit physical education requirement.* Independent fitness program as arranged with instructor, three times a week. Detailed proposals must be submitted in writing during first week of each term. Instructor: D'Auria.

PE 2 abc. Skin Diving. *3 units.* Fundamentals of skin diving and oceanography. Instructor: Dodd.

PE 4 abc. Introduction to Power Walking. *3 units.* Introduction to walking for fitness. Emphasis on cardiovascular benefits for a healthy lifestyle. The program is progressive and suitable for walkers of all levels. Instructor: Levesque.

PE 6 abc. Core Training, Beginning/Intermediate. *3 units.* Learn to develop functional fitness using core stability training techniques that focus on working the deep muscles of the entire torso at once. The course is taught using exercises that develop core strength, including exercises on a stability ball, medicine ball, wobble boards as well as with Pilates exercise programs. Instructor: Staff.

PE 7 abc. Speed and Agility Training, Intermediate/Advanced. *3 units.* Instruction to increase foot speed and agility with targeted exercises designed to help the student increase these areas for use in competitive situations. Instruction will focus on increasing foot speed, leg turnover, sprint endurance, and competitive balance. Proper technique and specific exercises as well as the development of an individual or sport-specific training workout will be taught. Instructor: Staff.

PE 8 abc. Fitness Training, Beginning. *3 units.* An introductory class for students who are new to physical fitness. Students will be introduced to different areas of fitness such as weight training, core training, walking, aerobics, yoga, swimming, and cycling. Students will then be able to design an exercise program for lifelong fitness. Instructor: Staff.

PE 9 abc. Soccer. *3 units.* Fundamental instruction on shooting, passing, trapping, dribbling, penalty kicks, offensive plays, defensive strategies, and goal keeping. Class includes competitive play using small field and full field scrimmages. Instructor: Uribe.

PE 10 abc. Aerobic Dance. *3 units.* Each class includes a thorough warm-up, a cardiovascular workout phase that also includes a variety of conditioning exercises designed to tone and strengthen various muscle groups, and a relaxation cool-down and stretch, all done to music. Instructor: Staff.

PE 12 abc. Baseball Skills, Intermediate/Advanced. *3 units.* Baseball skills—including infield/outfield, pitcher/catcher, and batting drills—taught, leading to competitive play. Students must have experience in hard ball. Instructor reserves the right to exclude students who do not fit criteria. Instructor: D'Auria.

PE 14 abc. Basketball Skills, Beginning and Beginning/Intermediate. *3 units.* Features fundamental instruction on shooting, dribbling, passing, defensive positioning, and running an offense. Class includes competitive play and free-throw shooting. Instructors: Eslinger, Marbut.

PE 20 abc. Fencing, Beginning and Intermediate/Advanced. *3 units.* Beginning fencing includes basic techniques of attack, defense, and counter-offense. Lecture topics include fencing history, strategy, scouting and analysis of opponents, and gamesmanship. Intermediate/Advanced covers foil theory and techniques, group drillwork, and video analysis. Instructor: Staff.

PE 23 abc. Track and Field, Beginning. *3 units.* Features instruction on 10 different track events, allowing the student an opportunity to attempt a variety of skills: shot put, discus, javelin, sprints, hurdles, long jump, high jump, middle- and long-distance running, and the relays. Class emphasis placed on learning new skills safely with time devoted to warm-up and stretching, as well as weight training for specific events. Instructor: Levesque.

PE 24 abc. Yoga, Beginning. *3 units.* Hatha Yoga is a system of physical postures designed to stretch and strengthen the body, calm the nervous system, and center the mind. It is a noncompetitive activity designed to reduce stress for improved health of body and mind while increasing flexibility, strength, and stamina, and reducing the chance of athletic injury. Instructor: Staff.

PE 27 abc. Ultimate Frisbee. *3 units.* Instruction will center on developing students' knowledge of techniques, rules, strategy, etiquette, and safety regulations of the game. Students will develop the ability to perform all the skills necessary to play the game confidently on a recreational basis. Instructor: Staff.

PE 30 abc. Golf, Beginning, Intermediate, and Advanced. *3 units.* Beginning class covers fundamentals of the game, including rules, terminology, etiquette, basic grip, set-up, swing, and club selection for each shot. The following shots will be covered: full swing (irons and woods), chip, pitch, sand, and putting. Intermediate class will focus on swing development of specialty shots and on course play management. Advanced instruction covers course management and mental aspects of performance. Instructor: Staff.

PE 35 abc. Diving, Beginning/Intermediate. *3 units.* Teaches the fundamentals of springboard diving to include basic approach, and five standard dives. Intermediate class includes instruction in the back somersault, forward somersault, forward somersault full twist, and reverse somersault. Instructor: Dodd.

PE 36 abc. Swimming, Beginning/Intermediate and Advanced. *3 units.* Instruction in all basic swimming strokes, including freestyle, elementary backstroke, racing backstroke, breaststroke, sidestroke, and butterfly. Advanced class focuses on proper technique of the four competitive strokes using video and drills along with instruction on training methods and proper workout patterns. Instructor: Dodd.

PE 38 abc. Water Polo. *3 units.* Basic recreational water polo with instruction of individual skills and team strategies. A background in swimming is encouraged. Instructor: Staff.

PE 40 abc. Dance Dance Revolution. *3 units.* Dance-rhythm game emphasizing speed and accuracy of footwork. Basic skills in rhythm and coordination will be taught and developed with play. Intermediate instruction will expand on these skills and focus on higher-level techniques and stamina. Instructor: Staff.

PE 44 abc. Karate (Shotokan), Beginning and Intermediate/Advanced. *3 units.* Fundamental self-defense techniques including form practice and realistic sparring. Emphasis on improving muscle tone, stamina, balance, and coordination, with the additional requirement of memorizing one or more simple kata (forms). Instructor: Staff.

PE 46 abc. Karate (Tang Soo Do), Beginning and Intermediate/Advanced. *3 units.* Korean martial art focusing on self-defense and enhancement of physical and mental health. Practical and traditional techniques such as kicks, blocks, hyungs (forms) are taught. Intermediate/Advanced level incorporates technique combinations, sparring skills, jumping and spinning kicks, and history and philosophy. Instructor: Staff.

PE 48 abc. T'ai-Chi Ch'uan, Beginning and Intermediate/Advanced. *3 units.* Chinese movement art emphasizing relaxation and calm awareness through slow, flowing, meditative movement using only the minimum of strength needed to accomplish the action. Instructor: Staff.

PE 50 abc. Badminton, Beginning/Intermediate. *3 units.* Basic skills will be taught, including grips, services, overhead and underhand strokes, and footwork. Rules, terminology, and etiquette are covered. Intermediate skills such as drives, service returns, forehand and backhand smash returns, attacking clears, and sliced drop shots are taught. Singles and doubles play along with drill work throughout the term. Instructor: Staff.

PE 54 abc. Racquetball, Beginning and Intermediate/Advanced. *3 units.* Fundamentals of the game will be emphasized, including rules, scoring, strategy, and winning shots. All types of serves will be covered, as well as a variety of shots to include kill, pinch-off, passing, ceiling, and off-the-backwall. Singles and doubles games will be played. Intermediate/Advanced course will review all fundamentals with a refinement of winning shots and serves and daily games. Instructor: Staff.

PE 56 abc. Squash, Beginning, Intermediate, Advanced. *3 units.* Learn by playing as the basic rules and strokes are taught. Fundamentals to include proper grip, stroke, stance, and positioning, along with serve and return of serve. Intermediate and Advanced classes will concentrate on skill development with the inclusion of forehand and backhand drives, lobs, volleys, and drops, with an emphasis on court movement, shot selection, and tactics. Instructor: Staff.

PE 60 abc. Tennis, Beginning, Intermediate, and Advanced. *3 units.* Stroke fundamentals, singles and doubles play, plus rules, terminology, and etiquette are covered in all classes. Beginning class emphasizes groundstrokes, volleys, serve, and grips. Beginning/Intermediate class is for those players caught between levels and will concentrate on strategy, drills, and match play. Intermediate level focuses on improving technique, footwork, and court positioning, with instruction on approach shots, volleys, overheads, and lobs. Advanced course fine tunes each individual's skills while targeting weaknesses. Instructors: D'Auria, Gamble, Uribe.

PE 70 abc. Weight Training, Beginning/Intermediate. *3 units.* Active participation in a strength and conditioning program designed for individual skill level and desired effect. Course will enlighten students on various methods, terminology, and techniques in the areas of isokinetic strength and cardiovascular fitness training. Instructor: Staff.

PE 77 abc. Volleyball, Beginning, Intermediate, and Advanced. *3 units.* Fundamental instruction on drills, strategies, and rules, with game-playing opportunity. Basics of serve, pass, set, spike, defense, and court position will be taught. Intermediate level focuses on skill development to a more competitive standard and features multiple offenses and understanding officiating. Advanced class emphasizes specialization of all skills, court position, and multiple offenses and defenses. Instructor: Staff.

PE 80 abc. Health Advocates. *3 units (1-1-1); first, second, third terms.* A course designed to involve students with health care and education, develop familiarity with common college health problems, and provide peer health services on and off campus. First term: CPR and first aid certification and basic anatomy and physiology. Second and third terms: lectures and discussions on current student and community health problems, symptoms, and treatment. Each student will be expected to devote one hour per week to a supervised clinical internship at the Health Center. *Does not satisfy the Institute physical education requirement.* Instructor: Staff.

PE 82 abc. Rock Climbing, Beginning and Intermediate. *3 units.* Basic skills will be covered to utilize each student's strength and endurance while learning to climb safely. Use of climbing rope and other equipment for belaying, rappelling, and emergency ascent will be taught. Skills will be demonstrated and practiced on a climbing wall and then later at an off-campus climbing site. Intermediate level will include ascents on prussiks or jumars, with more off-campus climbing. Instructor: Staff.

PE 84 abc. Table Tennis, Beginning, Intermediate, and Advanced. *3 units.* Introductory course to provide general knowledge of equipment, rules, and basic strokes, including topspin drive, backspin chop, and simple block in both forehand and backhand. Multiball exercise utilizing robot machines and video. Intermediate class covers regulations for international competition and fundamentals of winning table tennis, including footwork drills, smash, serve, and attack. Instructor: Staff.

Intercollegiate Teams

PE 83 abc. Intercollegiate Basketball Team (Women). *3 units.* Coach: Marbut.

PE 85 abc. Intercollegiate Track and Field Team (Men and Women). *3 units.* Coach: Levesque.

PE 87 abc. Intercollegiate Swimming Team (Men and Women). *3 units.* Coach: Dodd.

PE 89 abc. Intercollegiate Fencing Team (Men and Women). *3 units.* Coach: D'Asaro.

PE 90 abc. Intercollegiate Water Polo Team (Men and Women). *3 units.* Coach: Moser.

PE 91 abc. Intercollegiate Basketball Team (Men). *3 units.* Coach: Eslinger.

PE 92 abc. Intercollegiate Soccer Team (Men). *3 units.* Coach: Uribe.

PE 93 abc. Intercollegiate Baseball Team (Men). *3 units.* Coach: D'Auria.

PE 95 abc. Intercollegiate Tennis Team (Men). *3 units.* Coach: Gamble.

PE 96 abc. Intercollegiate Tennis Team (Women). *3 units.* Coach: Gamble.

PE 97 abc. Intercollegiate Cross-Country Team (Men and Women). *3 units.* Coach: Jung.

PE 99 abc. Intercollegiate Volleyball Team (Women). *3 units.* Coach: Colon.

PHYSICS

Ph 1 abc. Classical Mechanics and Electromagnetism. *9 units (4-0-5); first, second, third terms.* The first year of a two-year course in introductory classical and modern physics. Topics: Newtonian mechanics in Ph 1 a; electricity and magnetism, and special relativity, in Ph 1 b, c. Emphasis on physical insight and problem solving. Ph 1 b, c is divided into two tracks: the Practical Track emphasizing practical electricity, and the Analytic Track, which teaches and uses methods of multivariable calculus. Students enrolled in the Practical Track are encouraged to take Ph 8 bc concurrently. Students will be given information helping them to choose a track at the end of fall term. Instructors: Zmuidzinas, Harrison, Politzer, Filippone.

Ph 2 ab. Waves, Quantum Mechanics, and Statistical Physics. *9 units (4-0-5); first, second terms. Prerequisites: Ph 1 abc, Ma 1 abc, or equivalents.* The second year of a five-term introductory course in classical and modern physics. Topics to be covered include waves and introductory quantum mechanics first term, statistical physics second term. Instructors: Martin, Adhikari, Filippone.

Ph 3. Physics Laboratory. *6 units; first, second, third terms. Prerequisite: Ph 1 a or instructor's permission.* An introduction to experimental technique, commonly used in the physical sciences. A variety of topics is presented, including the Maxwell top, electrical and mechanical resonant systems, and radioactivity. Special emphasis is given to data analysis techniques based on modern statistical methods. The course consists of one three-hour laboratory session a week, conferences with the instructor, prelaboratory preparation, and analysis of experimental results. Graded pass/fail; seniors receive letter grades. Only one term may be taken for credit. Instructors: Sannibale, Libbrecht.

Ph 5. Physics Laboratory. *9 units; first term. Prerequisites: Ph 1 abc, Ph 3, or equivalents.* A laboratory course dealing with "operational" electronics with emphasis on analog electronics. The following topics are studied: RC circuits, electrical oscillations, operational amplifiers, diodes, and transistors. Combining diodes, transistors, and operational amplifiers; computer data acquisitions. The course culminates in a two-week project of the student's choosing. Instructors: Rice, Sannibale, Libbrecht.

Ph 6. Physics Laboratory. *9 units; second term. Prerequisites: Ph 1 abc, Ph 2 b or Ph 12 b (or taken concurrently), and Ph 3 or equivalent.* Experiments in electromagnetic phenomena such as electromagnetic induction, properties of magnetic materials, and high-frequency circuits. Mobility of ions in gases; precise measurement of the value of e/m of the electron. Instructors: Rice, Libbrecht.

Ph 7. Physics Laboratory. *9 units; third term. Prerequisite: Ph 6 or equivalent.* Experiments in atomic and nuclear physics, including studies of the Balmer series of hydrogen and deuterium, the decay of radioactive nuclei, absorption of X rays and gamma rays, ratios of abundances of isotopes, and the Stern-Gerlach experiment. Instructors: Rice, Libbrecht.

Ph 8 bc. Experiments in Electromagnetism. *3 units (0-3-0); second, third terms. Prerequisite: Ph 1 a.* A two-term sequence of experiments that parallel the material of Ph 1 bc. It includes measuring the force between wires with a homemade analytical balance, measuring properties of a 1,000-volt spark, and building and studying a radio-wave transmitter and receiver. The take-home experiments are constructed from a kit of tools and electronic parts. Measurements are compared to theoretical expectations. Instructor: Pine.

Ph 10. Frontiers in Physics. *3 units (2-0-1); first term. Open for credit to freshmen and sophomores.* Weekly seminar by a member of the physics department or a visitor, to discuss his or her research at an introductory level; the other class meetings will be used to explore background material related to seminar topics and to answer questions that arise. The course will also help students find faculty sponsors for individual research projects. Graded pass/fail. Instructor: Prince.

Ph 11 abc. Research Tutorial. *6 units (2-0-4); second and third terms of freshman year and first term of sophomore year.* A small number of students will be offered the opportunity to enroll in this tutorial, the purpose of which is to demonstrate how research ideas arise, and are evaluated and tested, and how those ideas that survive are developed. This is accomplished by doing individual, original projects. There will be weekly group meetings and individual tutorial meetings with the instructor. Support for summer research at Caltech between the freshman and sophomore years will be automatic for those students making satisfactory progress. Graded pass/fail. Instructor: Tombrello.

Ph 12 abc. Waves, Quantum Physics, and Statistical Mechanics. *9 units (4-0-5); first, second, third terms. Prerequisites: Ph 1 abc, Ma 1 abc, or* *equivalents.* A one-year course primarily for students intending further work in the physics option. Topics include classical waves; wave mechanics, interpretation of the quantum wave-function, one-dimensional bound states, scattering, and tunneling; thermodynamics, introductory kinetic theory, and quantum statistics. Instructors: Kimble, Refael, Preskill.

Ph 20, 21, 22. Computational Physics Laboratory. A series of courses on the application of computational techniques to simulate or solve simple physical systems, with the intent of aiding both physics understanding and programming ability. Instructors: Mach, Prince.

20. *6 units (0-6-0); first, second, third terms.* Introduction to scientific computing with applications to physics. Use of numerical algorithms and symbolic manipulation packages for solution of physical problems. Numerical integration and numerical solution of differential equations of motion. Simulation of orbital mechanics.

21. *6 units (0-6-0); second, third terms. Prerequisite: Ph 20 or equivalent experience with programming and numerical techniques.* Introduction to numerical algorithms for scientific computing. Root-finding, Runge-Kutta methods, Monte Carlo techniques, numerical solution of partial differential equations, minimization techniques such as neural networks. Applications to problems in classical mechanics and discrete-element electromagnetism.

22. *6 units (0-6-0); third term. Prerequisite: Ph 20 or equivalent experience with programming and numerical techniques.* Introduction to scientific computing on parallel computers. Introduction to parallel computing and multiprocessing. Message passing on networked workstations. Algorithm decomposition and parallelization. Numerical solution of N-body systems on multiprocessor computers.

Ph 50 abc. Caltech Physics League. *4 units (1-0-3); first, second, third terms. Prerequisite: Ph 1 abc.* This course serves as a physics club, meeting weekly to discuss and analyze real-world problems in the physical sciences. A broad range of topics will be considered, such as energy production, space and atmospheric phenomena, astrophysics, nano-science, and others. Students will use basic physics knowledge to produce simplified (and perhaps speculative) models of complex natural phenomena. In addition to regular assignments, students will also compete in solving challenge problems each quarter, with prizes given in recognition of the best solutions. Instructor: Refael.

Ph 70. Oral and Written Communication. *6 units (2-0-4); second, third terms.* Provides practice and guidance in oral and written communication of material related to contemporary physics research. Students will choose a topic of interest, make presentations of this material in a variety of formats, and, through a guided process, draft and revise a technical or review article on the topic. The course is intended for senior physics majors. *Fulfills the Institute scientific writing requirement.* Instructor: Hitlin.

Ph 77 abc. Advanced Physics Laboratory. *9 units (0-5-4); first, second, third terms. Prerequisite: Ph 7 or instructor's permission.* A three-term laboratory course to familiarize students with equipment and procedures used in the research laboratory. Experiments illustrate fundamental physical phenomena in atomic, optical, condensed-matter, nuclear, and particle physics, including NMR, laser-based atomic spectroscopy, gamma and X-ray spectroscopy, muon decay, weak localization, superconductivity, positron annihilation, and others. Instructors: Black, Libbrecht.

Ph 78 abc. Senior Thesis, Experimental. *9 units; first, second, third terms. Prerequisite: To register for this course, the student must obtain approval of the chair of the Physics Undergraduate Committee (Ed Stone). Open only to senior physics majors.* This research must be supervised by a faculty member, the student's thesis adviser. Laboratory work is required for this course. Two 15-minute presentations to the Physics Undergraduate Committee are required, one at the end of the first term and the second at the midterm week of the third term. The written thesis must be completed and distributed to the committee one week before the second presentation. Not offered on a pass/fail basis. See Note below.

Ph 79 abc. Senior Thesis, Theoretical. *9 units; first, second, third terms. Prerequisite: To register for this course, the student must obtain approval of the chair of the Physics Undergraduate Committee (Ed Stone). Open only to senior physics majors.* This research must be supervised by a faculty member, your thesis adviser. Two 15-minute presentations to the Physics Undergraduate Committee are required, one at the end of the first term and the second at the midterm week of the third term. The written thesis must be completed and distributed to the committee one week before the second presentation. Not offered on a pass/fail basis. See Note below.

Note: Students wishing assistance in finding an adviser and/or a topic for a senior thesis are invited to consult with the chair of the Physics Undergraduate Committee, or any other member of this committee. A grade will not be assigned in Ph 78 or Ph 79 until the end of the third term. P grades will be given the first two terms, and then changed at the end of the course to the appropriate letter grade.

Ph 101. Order-of-Magnitude Physics. *9 units (3-0-6); first term.* Emphasis will be on using basic physics to understand complicated systems. Examples will be selected from properties of materials, geophysics, weather, planetary science, astrophysics, cosmology, biomechanics, etc. Instructor: Phinney.

Ph 103 ab. Topics in Contemporary Physics. *9 units (3-0-6); first, second terms. Prerequisite: instructor's permission.* A series of introductory one-term, independent courses. Students may register for any particular term or terms.

a. Atomic and Molecular Spectroscopy. *Second term.* This course will review the basic spectroscopy of atoms and molecules, with applications to astrophysics, the terrestrial atmosphere, and the laboratory. Species to be discussed include hydrogen and simple multielectron atoms such as carbon, diatomic and polyatomic molecules, and some solids. Mechanisms and effects determining linewidths and lineshapes will be discussed for laboratory, atmospheric, and astrophysical conditions. Instructor: Phillips.

Ph/Bi 103 b. Neuroscience for Physicists and Engineers. *First term.* A reading and discussion course on topics ranging from the function of single neurons to methods for studying multineural activity in synapses; electrical recording; vision; positron and NMR topography; and neural modeling. Preference is given to physics seniors. Instructor: Pine.

Ay/Ph 104. Relativistic Astrophysics. *9 units (3-0-6).* For course description, see Astrophysics.

Ph 105. Analog Electronics for Physicists. *9 units; first term. Prerequisites: Ph 1 abc, Ph 3, or equivalents (the take-home lab of Ph 1 bc may be substituted for Ph 3).* A laboratory course dealing with "operational" electronics with emphasis on analog electronics. The following topics are studied: RC circuits, electrical oscillations, operational amplifiers, diodes, and transistors. Combining diodes, transistors, and operational amplifiers; computer data acquisition. The course culminates in a two-week project of the student's choosing. Instructors: Rice, Sannibale, Libbrecht.

Ph 106 abc. Topics in Classical Physics. *9 units (3-0-6); first, second, third terms. Prerequisites: Ph 2 ab or Ph 12 abc, Ma 2.* An intermediate course in the application of basic principles of classical physics to a wide variety of subjects. Roughly half of the year will be devoted to mechanics, and half to electromagnetism. Topics include Lagrangian and Hamiltonian formulations of mechanics, small oscillations and normal modes, boundary-value problems, multipole expansions, and various applications of electromagnetic theory. Instructors: Cross, Eisenstein.

APh/Ph 115 ab. Physics of Transport in Fluids. *9 units (3-0-6).* For course description, see Applied Physics.

Ph/EE 118. Low-Noise Electronic Measurement. *9 units (3-0-6); second term. Prerequisite: Ph 105 or equivalent.* An introduction to ultralow-noise electrical measurements and sensor technology as applied to experimental research. Topics include physical noise processes, signal transduction, synchronous and lock-in detection, digital signal transforms, and other aspects of precision measurements. Specific sensor technologies will include SQUID sensors, single electron transistors, transition-edge sensors, tunnel junction detectors, micro- and nanomechanical detectors, and biosensors. Instructor: Roukes.

Ph 125 abc. Quantum Mechanics. *9 units (3-0-6); first, second, third terms. Prerequisites: Ma 2 ab, Ph 12 abc or Ph 2 ab, or equivalents.* A one-year course in quantum mechanics and its applications, for students who have completed Ph 12 or Ph 2. Wave mechanics in 3-D, scattering theory, Hilbert spaces, matrix mechanics, angular momentum, symmetries, spin-1/2 systems, approximation methods, identical particles, and selected topics in atomic, solid-state, nuclear, and particle physics. Instructor: Wise.

Ph 127 abc. Statistical Physics. *9 units (3-0-6); first, second, third terms. Prerequisites: Ph 12 c or equivalent, and a basic understanding of quantum and classical mechanics.* A course in the fundamental ideas and applications of classical and quantum statistical mechanics. Topics to be covered include the statistical basis of thermodynamics; ideal classical and quantum gases (Bose and Fermi); lattice vibrations and phonons; weak interaction expansions; phase transitions; and fluctuations and dynamics. Instructor: Motrunich.

Ph 129 abc. Mathematical Methods of Physics. *9 units (3-0-6); first, second, third terms. Prerequisites: Ph 106 abc and ACM 95/100 abc or Ma 108 abc, or equivalents.* Mathematical methods and their application in physics. First term includes analytic and numerical methods for solving differential equations, integral equations, and transforms, and other applications of real analysis. Second term focuses on probability and statistics in physics. Third term covers group theoretic methods in physics. The three terms can be taken independently. Instructors: Porter, Refael, Schwarz.

Ph 134. String Theory. *9 units (3-0-6); third term. Prerequisites: Ph 125 ab, Ph 106 ab.* A basic course in string theory designed to be accessible to a broad audience. The main topics include the motion of relativistic point particles and strings, actions, world-sheet symmetries and currents, light-cone quantization, and the spectra of relativistic open and closed strings. The course will conclude with an exploration of D-branes, T-duality, or string thermodynamics, depending on student interest. Not offered 2010–11.

Ph 135 abc. Applications of Quantum Mechanics. *9 units (3-0-6); first, second, third terms. Prerequisite: Ph 125 abc or equivalent.* Applications of quantum mechanics to topics in contemporary physics. Particle physics, condensed-matter physics, and quantum phenomena in the early universe will be offered first, second, third terms, respectively. Terms may be taken independently. Instructors: Weinstein, Fisher, Kamionkowski.

Ph 136 abc. Applications of Classical Physics. *9 units (3-0-6); first, second, third terms. Prerequisite: Ph 106 abc or equivalent.* Applications of classical physics to topics of interest in contemporary "macroscopic" physics. Continuum physics and classical field theory; elasticity and hydrodynamics; plasma physics; magnetohydrodynamics; thermodynamics and statistical mechanics; gravitation theory, including general relativity and cosmology; modern optics. Content will vary from year to year, depending on the instructor. An attempt will be made to organize the material so that the terms may be taken independently. Not offered 2010–11.

Ph 171. Reading and Independent Study. *Units in accordance with work accomplished.* Occasionally, advanced work involving reading, special problems, or independent study is carried out under the supervision of an instructor. Approval of the instructor and of the student's departmental adviser must be obtained before registering. Graded pass/fail.

Ph 172. Research in Experimental Physics. *Units in accordance with work accomplished.* Approval of the student's research supervisor and department adviser must be obtained before registering. Graded pass/fail.

Ph 173. Research in Theoretical Physics. *Units in accordance with work accomplished.* Approval of the student's research supervisor and departmental adviser must be obtained before registering. Graded pass/fail.

BE/APh/Ph 181. Biological Interfaces, Transduction, and Sensing. *9 units (3-0-6).* For course description, see Bioengineering.

CNS/Bi/Ph/CS 187. Neural Computation. *9 units (3-0-6).* For course description, see Computation and Neural Systems.

Ph 199. Frontiers of Fundamental Physics. *9 units (3-0-6); third term. Prerequisites: Ph 125 abc, Ph 106 abc, or equivalent.* This course will explore the frontiers of research in particle physics and cosmology, focusing on physics at the Large Hadron Collider. Topics include the experimental search for the Higgs boson, supersymmetry and extra dimensions, and the study of the relevant Standard Model backgrounds. The course is geared toward seniors and first-year graduate students who are not in particle physics, although students in particle physics are welcome to attend. Instructor: Spiropulu.

Ph 205 abc. Relativistic Quantum Mechanics. *9 units (3-0-6); first, second, third terms. Prerequisite: Ph 125.* Topics: the Dirac equation, second quantization, quantum electrodynamics, scattering theory, Feynman diagrams, non-Abelian gauge theories, Higgs symmetry-breaking, the Weinberg-Salam model, and renormalization. Instructors: Schwarz, Gukov.

Ph 210. Theoretical Quantum Chromodynamics. *9 units (3-0-6); third term. Prerequisite: Ph 205 ab.* Applications of quantum field theory to quantum chromodynamics, including operator product expansion, twist expansion and applications to deep inelastic scattering and Drell-Yan; effective field theories, including chiral perturbation theory, heavy quark effective theory, and soft collinear effective theory; large Nc; introduction to lattice chromodynamics. Applications to strong interaction phenomenology and weak decays. Not offered 2010–11.

Ph 217 abc. Introduction to the Standard Model. *9 units (3-0-6); first, second, third terms. Prerequisites: Ph 205 abc and Ph 236 abc, or equivalent.* This course deals with elementary particle physics and cosmology. Students should have at least some background in quantum field theory and general relativity. The standard model of weak and strong interactions is developed, along with predictions for Higgs physics and flavor physics. Some conjectures for physics beyond the standard model are introduced: for example, low-energy supersymmetry and warped extra dimensions. In the second half of the course, the standard picture for cosmology is discussed. The predictions of inflation for the primordial density perturbations are reviewed. The microwave background anisotropy is discussed. Not offered 2010–11.

Ph/CS 219 abc. Quantum Computation. *9 units (3-0-6); first, second terms. Prerequisite: Ph 129 abc or equivalent.* The theory of quantum information and quantum computation. Overview of classical information theory, compression of quantum information, transmission of quantum information through noisy channels, quantum error-correcting codes, quantum cryptography and teleportation. Overview of classical complexity theory, quantum complexity, efficient quantum algorithms, fault-tolerant quantum computation, physical implementations of quantum computation. Instructors: Kitaev, Preskill.

Ph/APh 223 abc. Advanced Condensed-Matter Physics. *9 units (3-0-6); first, second, third terms. Prerequisite: Ph 125 or equivalent, or instructor's permission.* Advanced topics in condensed-matter physics, emphasizing the application of formal quantum field theory and group theory methods to many-body systems. Selected topics may include path integral and canonical formalisms, Green's function techniques and Feynman diagrams, Fermi liquid theory, Luttinger liquid theory, symmetry breaking and Landau-Ginzburg theory of phase transitions, group theory and its applications, field theory for interacting bosons and superfluidity, superconductivity, Kondo effect, Hubbard and t-J models, gauge theory, fractional quantum Hall effect, anyons, and topological field theory. Not offered 2010–11.

Ph 229 abc. Advanced Mathematical Methods of Physics. *9 units (3-0-6); first, second terms. Prerequisite: Ph 129 abc or equivalent.* Advanced topics in geometry and topology that are widely used in modern theoretical physics. Emphasis will be on understanding and applications more than on rigor and proofs. First term will cover basic concepts in topology and manifold theory. Second term will include Riemannian geometry, fiber bundles, characteristic classes, and index theorems. Third term will include anomalies in gauge-field theories and the theory of Riemann surfaces, with emphasis on applications to string theory. Instructor: Ooguri.

Ph 230 abc. Elementary Particle Theory. *9 units (3-0-6); first, second, third terms. Prerequisite: Ph 205 abc or equivalent.* Advanced methods in quantum field theory. First term: introduction to supersymmetry, including the minimal supersymmetric extension of the standard model, supersymmetric grand unified theories, extended supersymmetry, supergravity, and supersymmetric theories in higher dimensions. Second and third terms: nonperturbative phenomena in non-Abelian gauge field theories, including quark confinement, chiral symmetry breaking, anomalies, instantons, the 1/N expansion, lattice gauge theories, and topological solitons. Not offered 2010–11.

Ph 231 abc. Elementary Particle Physics. *9 units (3-0-6); first, second, third terms. Prerequisite: Ph 125 or equivalent.* An introduction to elementary particle physics, stressing experimental phenomena and their theoretical interpretations. The standard model and its confrontation with experiment will be covered. Current notions for particle physics beyond the standard model will be explored, along with possible experimental signatures. Experimental techniques will also be discussed, including an introduction to accelerator physics. Not offered 2010–11.

Ph 232. Introduction to Topological Field Theory. *9 units (3-0-6); second term. Prerequisite: Ph 205.* Topological field theories are the simplest examples of quantum field theories which, in a sense, are exactly solvable and generally covariant. During the past twenty years they have been the main source of interaction between physics and mathematics. Thus, ideas from gauge theory led to the discovery of new topological invariants for 3-manifolds and 4-manifolds. By now, topological quantum field theory (TQFT) has evolved into a vast subject, and the main goal of this course is to give an accessible introduction to this elegant subject. Instructor: Kitaev.

Ph 235 abc. Introduction to Supersymmetry and String Theory. *9 units (3-0-6); second, third terms. Prerequisite: Ph 205.* First term: introduction to supersymmetry. After explaining the basic concepts of supersymmetry, the emphasis will be on formulating and analyzing the minimal supersymmetric extension of the standard model and supersymmetric grand unified theories. There will also be brief introductions to supersymmetric theories in higher dimensions, theories with extended supersymmetry, and supergravity. Second term: introduction to superstring theory. Topics to be discussed include relativistic strings and their quantization, perturbative string theory, low energy effective supergravity theories, p-brane solutions and p-brane world volume theories, compactification of extra dimensions, M theory and F theory, dualities relating various superstring and M theory configurations, problems and prospects. Instructor: Kapustin.

Ph 236 abc. Relativity. *9 units (3-0-6); first, second, third terms. Prerequisite: a mastery of special relativity at the level of Goldstein's* Classical Mechanics, *or of Jackson's* Classical Electrodynamics. A systematic exposition of Einstein's general theory of relativity and its applications to gravitational waves, black holes, relativistic stars, causal structure of space-time, cosmology and brane worlds. Instructor: Chen.

Ph 237. Gravitational Waves. *9 units (3-0-6); third term. Prerequisite: Ph 236 a.* The theory and astrophysical phenomenology of gravitational-wave sources (black holes, neutron stars, compact binaries, early-universe phenomena, etc.). Gravitational-wave detectors (LIGO, LISA, and others), and data analysis. Not offered 2010–11.

Ph 242 ab. Physics Seminar. *3 units (2-0-1); first, second terms.* Topics in physics emphasizing current research at Caltech. One two-hour meeting per week. Speakers will be chosen from both faculty and students. Registration restricted to first-year graduate students in physics; exceptions only with permission of instructor. Graded pass/fail. Instructor: Stone.

Ph 250 abc. Introduction to String Theory. *9 units (3-0-6); first, second, third terms. Prerequisite: Ph 205 or equivalent.* The first two terms will focus largely on the bosonic string. Topics covered will include conformal invariance and construction of string scattering amplitudes, the origins of gauge interactions and gravity from string theory, T-duality, and D-branes. The third term will cover perturbative aspects of superstrings, supergravity, various BPS branes, and string dualities. Not offered 2010–11.

Ph 300. Thesis Research. *Units in accordance with work accomplished.* Ph 300 is elected in place of Ph 172 or Ph 173 when the student has progressed to the point where research leads directly toward the thesis for the degree of Doctor of Philosophy. Approval of the student's research supervisor and department adviser or registration representative must be obtained before registering. Graded pass/fail.

POLITICAL SCIENCE

PS 12. Introduction to Political Science. *9 units (3-0-6); first, third terms.* Introduction to the tools and concepts of analytical political science. Subject matter is primarily American political processes and institutions. Topics: spatial models of voting, redistributive voting, games, presidential campaign strategy, Congress, congressional-bureaucratic relations, and coverage of political issues by the mass media. Instructors: Ordeshook, Kiewiet.

PS 99 ab. Political Science Research Seminar. *9 units (3-0-6). Prerequisites: political science major; completion of a required PS course for major.* Development and presentation of a major research paper on a topic of interest in political science or political economy. The project will be one that the student has initiated in a political science course he or she has already taken from the PS courses required for the PS option, numbered above 101. This course will be devoted to understanding research in political science, and basic political science methodology. Students will be exposed to current research journals, work to understand a research literature of interest, and work to formulate a research project. *Fulfills the Institute scientific writing requirement.*

PS 101. Selected Topics in Political Science. *Units to be determined by arrangement with the instructor; offered by announcement.* Instructor: Staff.

PS 120. American Electoral Behavior and Party Strategy. *9 units (3-0-6); first term.* A consideration of existing literature on the voting behavior of the citizen, and an examination of theoretical and empirical views of the strategies followed by the parties. Instructor: Alvarez.

PS 121. Congressional Policy Formation and Legislative Process. *9 units (3-0-6).* Decision making in legislative bodies, with emphasis on the United States Congress. An investigation into the impact of congressional structure and practices on the policies adopted by the federal government. Not offered 2010–11.

PS 122. Political Representation. *9 units (3-0-6); second term. Prerequisite: PS 12.* Theory, practice, and consequence of political representation in the electoral context. Topics include the concept of representation; how the degree of representation of various groups and interests (such as ethnic and racial) is affected by different electoral rules; and the impact of representation of minorities on public policies. The primary focus is on the empirical literature pertaining to the United States, but examples from other countries are also examined for comparative purposes. Not offered 2010–11.

PS 123. Regulation and Politics. *9 units (3-0-6); first term. Prerequisite: PS 12.* This course will examine the historical origins of several regulatory agencies and trace their development over the past century or so. It will also investigate a number of current issues in regulatory politics, including the great discrepancies that exist in the cost-effectiveness of different regulations, and the advent of more market-based approaches to regulations instead of traditional "command-and-control." Not offered on a pass/fail basis. Instructor: Kiewiet.

PS 124. Political Economy. *9 units (3-0-6); third term.* The aim of this course is to introduce students to theoretical and applied research in political economy. The focus will be on formal analysis of the strategic interaction between rational individuals, political institutions, and economic outcomes. Some of the questions will be: Why do people vote? What are the incentives of elected politicians, and what is the effect of these incentives on the policies they will implement? To what extent do differences in political institutions account for differences in redistributive policies? Topics may include the theory of voting, models of direct democracy, models of electoral competition, the political economy of redistribution, and comparative political institutions. Instructor: Mattozzi.

BEM/PS 126. Business and Public Policy. *9 units (3-0-6).* For course description, see Business Economics and Management.

PS 130. Introduction to Social Science Surveys: Methods and Practice. *9 units (3-0-6); third term.* In this course, students will learn the basic methodologies behind social science survey analysis: self-completion and interview-assisted surveying, sampling theory, questionnaire design, theories of survey response, and the basic analysis and presentation of survey results will be covered, as well as contemporary research in survey methodology and public opinion analysis. Students will be involved in the active collection and analysis of survey data and the presentation of survey results; students will be required to complete an independent project involving some aspect of survey methodology. Not offered 2010–11.

PS 132. Formal Theories in Political Science. *9 units (3-0-6); first term. Prerequisite: PS 12 or equivalent.* Axiomatic structure and behavioral interpretations of game theoretic and social choice models and models of political processes based on them. Instructor: Agranov.

PS 135. Analyzing Legislative Elections. *9 units (3-0-6); second term.* The purpose of this course is to understand legislative elections. The course will study, for example, what role money plays in elections and why incumbents do better at the polls. It will also examine how electoral rules impact the behavior both of candidates and voters, and will explore some of the consequences of legislative elections, such as divided government. Not offered 2010–11.

PS/SS 139. Comparative Politics. *9 units (3-0-6); second term. Prerequisite: PS 12 or SS 13.* The politics of non-American political systems. Areas of study: the politics of nondemocratic states, including the Communist nations; the politics of developing societies; the politics of the Western European democracies. Emphasis on the effect of distinctive institutions on the performance of government and the content of public policy. Instructor: Ordeshook.

PS 141. A History of Budgetary Politics in the United States. *9 units (3-0-6); third term.* This class will examine budgetary conflict at key junctures in U.S. history. Topics include the struggle to establish a viable fiscal system in the early days of the Republic, the *ante bellum* tariff, the "pension politics" of the post–Civil War era, the growth of the American welfare state, and the battle over tax and entitlement reform in the 1980s and 1990s. Instructor: Kiewiet.

Law/PS/H 148 ab. The Supreme Court in U.S. History. *9 units (3-0-6).* For course description, see Law.

Ec/PS 160 abc. Laboratory Experiments in the Social Sciences. *9 units (3-3-3).* For course description, see Economics.

PS/Ec 172. Game Theory. *9 units (3-0-6); third term. Prerequisite: PS 12 or equivalent.* Axiomatic structure and behavioral interpretations of game theory models in social science. Axiomatic utility theory and general noncooperative games. Instructor: Ortoleva.

PS/Ec 173. Cooperation and Social Behavior. *9 units (3-0-6). Prerequisite: PS/Ec 172 or instructor's permission.* Game theoretic and evolutionary approaches to modeling various types of cooperative, altruistic, and social behavior. Emphasis on economic and political applications. Not offered 2010–11.

Ec/PS 190. Undergraduate Research. *Units to be arranged.* For course description, see Economics.

PSYCHOLOGY

Psy 15. Social Psychology. *9 units (3-0-6); third term.* The study of how people think about other people and behave toward or around others. Topics include attribution, social cognition, motivation and incentive, social influence, liking, stereotyping, deception, fairness and altruism, and conformity. Instructor: Paul.

Psy 16. Understanding Psychological Disorders. *9 units (3-0-6); first term.* A descriptive and theoretical survey of the major forms of psychopathology in children, adolescents, and adults. The course will examine current trends and research in the fields of mental health and psychopathology. Instructor: Paul.

Psy 20. Introduction to Cognitive Psychology. *9 units (3-0-6); second term.* This course will develop basic concepts in how humans process different kinds of information such as visual, auditory, and symbolic. These concepts will then be used to explore topics such as visual perception, attention and automaticity, working and long-term memory, imagery, knowledge representation, language acquisition and comprehension, judgement and choice, reasoning and decision making, problem solving, and group differences. Not offered 2010–11.

Psy 25. Reading and Research in Psychology. *Units to be determined by the instructor.* Written report required. Graded pass/fail. *Not available for credit toward humanities–social science requirement.* Not offered 2010–11.

Psy 101. Selected Topics in Psychology. *Units to be determined by arrangement with the instructor; offered by announcement.* Instructor: Staff.

CNS/SS/Psy/Bi 102 ab. Brains, Minds, and Society. *9 units (3-0-6).* For course description, see Computation and Neural Systems.

CNS/SS/Psy 110 abc. Cognitive Neuroscience Tools. *5 units.* For course description, see Computation and Neural Systems.

CNS/Bi/Psy 120. The Neuronal Basis of Consciousness. *9 units (4-0-5).* For course description, see Computation and Neural Systems.

Psy 125. Reading and Research in Psychology. Same as Psy 25, but for graduate credit. *Not available for credit toward humanities–social science requirement.*

Psy/CNS 130. Introduction to Human Memory. *9 units (3-0-6); second term.* The course offers an overview of experimental findings and theoretical issues in the study of human memory. Topics include iconic and echoic memory, working memory, spatial memory, implicit learning and memory; forgetting: facts vs. skills, memory for faces; retrieval: recall vs. recognition, context-dependent memory, semantic memory, spreading activation models and connectionist networks, memory and emotion, infantile amnesia, memory development, and amnesia. Not offered 2010–11.

CNS/Psy/Bi 131. The Psychology of Learning and Motivation. *9 units (3-0-6).* For course description, see Computation and Neural Systems.

CNS/Bi/SS/Psy 176. Cognition. *12 units (6-0-6).* For course description, see Computation and Neural Systems.

SS/Psy/Bi/CNS 255. Topics in Emotion and Social Cognition. *9 units (3-0-6).* For course description, see Social Science.

SOCIAL SCIENCE

SS 13. The Application of Social Scientific Methods to Problems in History. *9 units (3-0-6); first term.* The application of theory from economics, political science, and demography to historical subjects, with an emphasis on questions of institutional change. The historical topics covered will depend upon the instructor. Not offered 2010–11.

BEM/Ec/SS 20. Scientific Writing and Oral Presentation in the Social Sciences. *6 units (2-0-4).* For course description, see Business Economics and Management.

SS 98. Reading in Social Science. *Units to be determined for the individual by the department. Elective, in any term.* Reading in social science and related subjects, done either in connection with the regular courses or independently of any course, but under the direction of members of the department. A brief written report will usually be required. Graded pass/fail. *Not available for credit toward humanities–social science requirement.*

SS 101. Selected Topics in Social Science. *9 units (3-0-6); offered by announcement.* Not available for social science credit unless specifically approved by social science faculty. Instructors: Staff, visiting lecturers.

CNS/SS/Psy/Bi 102 ab. Brains, Minds, and Society. *9 units (3-0-6).* For course description, see Computation and Neural Systems.

CNS/SS/Psy 110 abc. Cognitive Neuroscience Tools. *5 units.* For course description, see Computation and Neural Systems.

H/SS 124. Problems in Historical Demography. *9 units (3-0-6).* For course description, see History.

Ec/SS 124. Introduction to Empirical Process Methods. *9 units (3-0-6).* For course description, see Economics.

Ec/SS 129. Economic History of the United States. *9 units (3-0-6).* For course description, see Economics.

Ec/SS 130. Economic History of Europe from the Middle Ages to the Industrial Revolution. *9 units (3-0-6).* For course description, see Economics.

PS/SS 139. Comparative Politics. *9 units (3-0-6).* For course description, see Political Science.

An/SS 142. Caltech Undergraduate Culture and Social Organization. *9 units (3-0-6).* For course description, see Anthropology.

CNS/Bi/SS/Psy 176. Cognition. *12 units (6-0-6).* For course description, see Computation and Neural Systems.

The graduate courses listed below are not necessarily taught each year. They will be offered as need dictates.

SS 200. Selected Topics in Social Science. *Units to be determined by arrangement with instructors; offered by announcement.* Instructors: Staff, visiting lecturers.

SS 201 abc. Analytical Foundations of Social Science. *9 units (3-0-6); first, second, third terms.* This course covers the fundamentals of utility theory, game theory, and social choice theory. These basic theories are developed and illustrated with applications to electoral politics, market trading, bargaining, auctions, mechanism design and implementation, legislative and parliamentary voting and organization, public economics, industrial organization, and other topics in economics and political science. Instructors: Ortoleva, Palfrey, Echenique.

SS 202 abc. Political Theory. *9 units (3-0-6); first, second, third terms.* Course will introduce the student to the central problems of political theory and analysis, beginning with the essential components of the democratic state and proceeding through a variety of empirical topics. These topics will include the analysis of electoral and legislative institutions, legislative agenda processes, voting behavior, comparative political economy, and cooperation and conflict in international politics. The student will be sensitized to the primary empirical problems of the discipline and trained in the most general applications of game theoretic reasoning to political science. Instructors: Palfrey, Snowberg, Alvarez.

SS 205 abc. Foundations of Economics. *9 units (3-0-6); first, second, third terms. Prerequisite: Ec 121 ab or instructor's permission.* This is a graduate course in the fundamentals of economics. Topics include comparative statics and maximization techniques, the neoclassical theory of consumption and production, general equilibrium theory and welfare economics, public goods and externalities, the economic consequences of asymmetric information and incomplete markets, and recursive methods with applications to labor economics and financial economics. Instructors: Border, Echenique, Ledyard.

SS 209. Behavioral Economics. *9 units (3-0-6); offered by announcement. Prerequisite: SS 201 abc or instructor's permission.* This course explores how psychological facts and constructs can be used to inform models of limits on rationality, willpower and greed, to expand the scope of economic analysis. Topics include overconfidence, heuristics for statistical judgment, loss-aversion, hyperbolic discounting, optimal firm behavior when consumers are limited in rationality, behavioral game theory, behavioral finance, neuroeconomic dual-self models, and legal and welfare implications of rationality limits. Not offered 2010–11.

SS 210 abc. Foundations of Political Economy. *9 units (3-0-6); first, second, third terms. Prerequisites: SS 202 c, SS 205 b.* Mathematical theories of individual and social choice applied to problems of welfare economics and political decision making as well as to the construction of political economic processes consistent with stipulated ethical postulates, political platform formulation, the theory of political coalitions, and decision making in political organizations. Instructors: Agranov, Yariv, Mattozzi.

SS 211 abc. Advanced Economic Theory. *9 units (3-0-6); first, second, third terms. May be repeated for credit.* Advanced work in a specialized area of economic theory, with topics varying from year to year according to the interests of students. Instructor: Echenique.

SS 212. Application of Microeconomic Theory. *9 units (3-0-6). May be repeated for credit.* A working seminar in which the tools of microeconomic theory are applied to the explanation of events and the evaluation of policy. Not offered 2010–11.

SS 213 abc. Financial Economics. *9 units (3-2-4); first, second, third terms.* First term: asset pricing theory, statistical tests on historical data and evidence from financial markets experiments. Second term: financial econometrics, with emphasis on applications to risk management. Third term: general equilibrium foundations of asset and option pricing theory. Instructor: Green.

SS/Ma 214. Mathematical Finance. *9 units (3-0-6); third term.* A course on fundamentals of the mathematical modeling of stock prices and interest rates, the theory of option pricing, risk management, and optimal portfolio selection. Students will be introduced to the stochastic calculus of various continuous-time models, including diffusion models and models with jumps. Instructor: Cvitanic.

SS 216. Interdisciplinary Studies in Law and Social Policy. *9 units (3-0-6); second term.* A policy problem or problems involving the legal system will be studied, using concepts from at least one social science discipline. Each offering will be taught by a law professor, alone or in conjunction with a member of the social science faculty. The topic will differ from term to term, so the course may be taken more than once. Selected undergraduates may enroll in this course with the permission of the instructor. Not offered 2010–11.

SS 218. Neuroscience Applications to Economics and Politics. *9 units (3-0-6); third term.* Topics in behavioral, affective, and social neuroscience that inform how individuals make economic decisions. Applications of neuroscience to understanding choice under risk and uncertainty, temporal discounting and self-control, advertisement and preference formation, addiction and other pathological behaviors, experienced utility, empathy, and trust. Instructors: Bossaerts, Camerer.

SS 222 abc. Econometrics. *9 units (3-0-6); first, second, third terms.* Introduction to the use of multivariate and nonlinear methods in the social sciences. Instructors: Shum, Gillen, Sherman.

SS 223 abc. Advanced Topics in Econometric Theory. *9 units (3-0-6); first, second terms. Prerequisite: SS 222 abc; may be repeated for credit.* A course in quantitative methods for second- and third-year social science graduate students. Instructors: Sherman, Shum.

SS 227. Identification Problems in the Social Sciences. *9 units (3-0-6). Prerequisite: SS 222 abc.* There is a tension in modeling social science phenomena between making strong assumptions, which lead to descriptive or normative conclusions that are precise when the assumptions hold but invalid when they do not hold, and making weak assumptions, which lead to less precise conclusions but hold more generally. The preponderance of social science research to date takes the former approach. This course studies recent advances in the latter approach. The course will review the work of Manski on bounds identification and estimation and trace some of the developments in this line of research to the present. Various applications of the methodology will be considered, including applications to Stanford-9 test-score data and data on organic pollutants in the Love Canal. Not offered 2010–11.

SS 228. Applied Data Analysis for the Social Sciences. *9 units (3-0-6); third term.* The course covers issues of management and computation in the statistical analysis of large social science databases. Maximum likelihood and Bayesian estimation will be the focus. This includes a study of Markov Chain Monte Carlo (MCMC) methods. Substantive social science problems will be addressed by integrating programming, numerical optimization, and statistical methodology. Not offered 2010–11.

SS 229 abc. Theoretical and Quantitative Dimensions of Historical Development. *9 units (3-0-6); first, second terms. May be repeated for credit.* Introduction to modern quantitative history. The tools of economic and political theory applied to problems of economic, social, and political development in a historical context. Second and third terms will be graded together. A pass/fail will be assigned in the second term and then changed to the appropriate letter grade at the end of the third term. Instructor: Rosenthal.

SS 231 abc. American Politics. *9 units (3-0-6); first, second, third terms.* A three-term course in American politics and political behavior. While drawing from contemporary materials, the course will emphasize the historical background of American political institutions. Instructor: Alvarez.

SS 232 abc. Historical and Comparative Perspectives in Political Analysis. *9 units (3-0-6); second term.* Provides a knowledge and understanding of developments in both the American past and in other parts of the world. Instructors: Snowberg, Katz.

SS 240. Techniques of Policy Research. *9 units (3-0-6). Prerequisite: SS 205 ab.* The application of social science theory and methods to the formulation and evaluation of public policy. Not offered 2010–11.

SS/CS 241 ab. Introduction to Social and Information Sciences. *9 units (3-0-6); second, third terms. Undergraduates cannot use this course towards fulfilling the core Institute social science requirement.* Introduction to techniques and methods used in research at the intersection of social and information sciences: aggregation of dispersed information and optimal allocation of resources through markets, networks, and other social systems; formation and off-equilibrium behavior of these systems; distributed cognition; related computational issues; aggregation, allocation, formation, and equilibration enhancements through technology—hardware and software, economic theory applied to the design of communication networks and computational systems; distributed information systems supporting economic activity. Instructors: EAS and HSS faculty. Not offered 2010–11.

CNS/SS 251. Human Brain Mapping: Theory and Practice. *9 units (3-1-5).* For course description, see Computation and Neural Systems.

SS/Psy/Bi/CNS 255. Topics in Emotion and Social Cognition. *9 units (3-0-6); third term. Prerequisite: Bi/CNS 150 or instructor's permission.* This course will cover recent findings in the psychology and neurobiology of emotion and social behavior. What role does emotion play in other cognitive processes, such as memory, attention, and decision making? What are the component processes that guide social behavior? To what extent is the processing of social information domain-specific? Readings from the current literature will emphasize functional imaging, psychophysical, and lesion studies in humans. Not offered 2010–11.

SS 260. Experimental Methods of Political Economy. *9 units (3-3-3).* Survey of laboratory experimental research related to the broad field of political economy. Topics: the behavior of markets, organizations, committee processes, and election processes. Emphasis on experimental methods and techniques. Students will design and conduct experiments. May be repeated for credit with instructor's permission. Instructor: Plott.

SS 280. Modern Topics in Social Science. *9 units (3-0-6); first term.* This course will teach students about the major modern contributions of social science in fields outside their areas of specialization. Students will cover a series of basic topics by reading and discussing the central papers or books that characterize what is known about each topic area. Different sections of the course will be offered in different social sciences (e.g., economics and political science). Instructor: Camerer.

SS 281. Graduate Social Science Writing Seminar. *9 units (3-0-6); third term.* Only open to advanced graduate students in social science. How can social scientists write in a style that makes someone actually want to read their papers? This seminar combines writing exercises with help in planning a professional social science paper and with extensive comments on drafts. Instructor: Kousser.

SS 283 abc. Graduate Proseminar in Social Science. *3 units (2-0-1); first, second, third terms.* Course for graduate students in social sciences. Students present their research and lead discussion of material relevant to their research program. Instructor: Rosenthal.

SS 300. Research in Social Science. *Units to be arranged.*