

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

AEROSPACE

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 11 abc, and ME 12 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; and acoustics. Instructor: Pullin, Austin.

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: Kochmann, Ravichandran, Bhattacharya.

Ae/APh 104 abc. Experimental Methods. *9 units (3-0-6) first term; (0-6-3) second, third terms. Prerequisites: ACM 95/100 ab 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: ME 11 abc and ME 12 abc 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 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: Davis, Freeman, Scharf.

CE/Ae/AM 108 ab. 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 2015–16.

APh/Ph/Ae 116. Physics of Thermal and Mass Transport in Hydrodynamic Systems. 12 units (3-0-9), *second term.* For course description, see Applied Physics.

Ae/ME 118. Classical Thermodynamics. 9 units (3-0-6); *first term. Prerequisites: ME 11 abc, ME 12, or equivalent.* Fundamentals of classical thermodynamics. Basic postulates and laws of thermodynamics, work and heat, entropy and available work, and thermal systems. Equations of state, compressibility functions, and the Law of Corresponding States. Thermodynamic potentials, chemical and phase equilibrium, phase transitions, and thermodynamic properties of solids, liquids, and gases. Examples will be drawn from fluid dynamics, solid mechanics, and thermal science applications. Not offered 2015–2016.

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. Not offered 2015–2016.

Ae 121 abc. Space Propulsion. 9 units (3-0-6); *each term. Open to all graduate students and to seniors with instructor's permission.* Ae 121 is designed to introduce the fundamentals of chemical, electric and advanced propulsion technologies. The course focuses on the thermochemistry and aerodynamics of chemical and electrothermal propulsion systems, the physics of ionized gases and electrostatic and electromagnetic processes in electric thrusters. These analyses provide the opportunity to introduce the basic concepts of non-equilibrium gas dynamics and kinetic theory. Specific technologies such as launch vehicle rocket engines, monopropellant engines, arcjets, ion thrusters, magnetoplasmadynamic engines and Hall thrusters will be

discussed. Ae 121 also provides an introduction to advanced propulsion concepts such as solar sails and antimatter rockets. 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: McKeon.

EE/Ae 157 ab. Introduction to the Physics of Remote Sensing. 9 units (3-0-6); first, second terms. 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. Instructor: Breckinridge.

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: Kochmann.

Ae/CE 165 ab. Mechanics of Composite Materials and Structures. 9 units (2-2-5); first, second 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

laminates using composite design software, hand layup of a simple laminate and measurement of its stiffness and thermoelastic coefficients. Pellegrino.

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 ab. Advanced Fluid Mechanics. *9 units (3-0-6); first, second terms. Prerequisites: Ae/APh/CE/ME 101 abc or equivalent; AM 125 abc or ACM 101 (may be taken concurrently).* Foundations of the mechanics of real fluids. Basic concepts will be emphasized. Subjects covered will include a selection from 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. Instructors: Pullin, Meiron.

Ae 204. Technical Fluid Mechanics. *9 units (3-0-6); first term. 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 2015-16.

Ae 205 ab. Advanced Space Project. *9 units (2-4-3); second, third terms. Prerequisites: Ae105 abc.* This is an advanced course on the design and implementation of space projects and it is currently focused on the flight project Autonomous Assembly of a Reconfigurable Space Telescope (AAR-eST). The objective is to be ready for launch and operation in 2015. Each student will be responsible for a specific activity, chosen from the following: optimization of telescope system architecture; design, assembly and testing of telescope optics; telescope calibration procedure and algorithms for wavefront control; thermal analysis; boom design and deployment test methods; effects of spacecraft dynamics on telescope performance; environmental testing of telescope system. Each student will prepare a survey of the state of the art for the selected activity, and then develop a design/implementation plan, execute the plan and present the results in a final report. Instructor: Pellegrino.

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: Kochmann, Austin.

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 nonmetallic solids. Mechanics of brittle and ductile fracture; connections between the continuum descriptions of fracture and micromechanisms. Discussion of elastic-plastic fracture analysis and fracture criteria. Special topics include fracture by cleavage, void growth, rate sensitivity, crack deflection and toughening mechanisms, as well as fracture of nontraditional materials. Fatigue crack growth and life prediction techniques will also be discussed. In addition, "dynamic" stress wave dominated, failure initiation growth and arrest phenomena will be covered. This will include traditional dynamic fracture considerations as well as discussions of failure by adiabatic shear localization. Instructor: Ortiz.

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 2015-16.

Ae/AM/ME 215. Dynamic Behavior of Materials. 9 units (3-0-6); second 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 2015-16.

Ae/ME 218. Statistical Mechanics. 3-0-6; second term. Prerequisites: Ae/ME118, or equivalent. Overview of probability and statistics, and the Maxwell-Boltzmann distribution. Overview and elements of Quantum Mechanics, degenerate energy states, particles in a box, and energy-state phase space. Statistics of indistinguishable elementary particles, Fermi-Dirac and Bose-Einstein statistics, partition functions, connections with classical thermodynamics, and the Law of Equipartition. Examples from equilibrium in fluids, solid-state physics, and others. Not offered 2015-2016.

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. Not offered 2015-16.

Ae/CE 221. Space Structures. 9 units (3-0-6); first 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. Not offered 2015-2016.

Ae/AM/ME 223. Plasticity. 9 units (3-0-6); third 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: Ortiz.

Ae/AM/ME 225. Special Topics in Solid Mechanics. Units to be arranged; first, second, third terms. Subject matter changes depending upon staff and student interest. (1) Stress Waves in Solids. 9 units (3-0-6); second term. Stress waves will be introduced by considering plane waves which allow the principal features of stress wave propagation to be explored without introducing the geometric complexities of waves in 3D. Formulation will include elastic materials and dissipative materials that are modeled as viscoelastic or viscoplastic. For elastic materials, we will consider waves in unbounded anisotropic media, refraction at plane boundaries, surface waves, wave guides, phase velocity and group velocity, waves in periodic media, energy transport, and diffraction. For dissipative materials, we will consider frequency-dependent attenuation, elastic precursor decay, and nonlinear waves in 1D. Examples, and opportunities to explore more advanced

topics, will be chosen to try to respond to student interests. Not offered 2015–2016.

Ae 228. Computational Mechanics Simulations Using Particles. 9 units (3–0–6); second 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 2015–16.

Ae/ACM/ME 232 ab. Computational Fluid Dynamics. 9 units (3–0–6); first, second 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. Not offered 2015–2016.

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 2015–2016.

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 2015–16.

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 2015–16.

Ae 237 a. Nonsteady Gasdynamics. 9 units (3-0-6); second term. 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 2015-16.

Ae 239 ab. Turbulence. 9 units (3-0-6); second, third terms. Prerequisites: Ae/APh/CE/ME 101 abc; AM 125 abc or ACM 101. 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. Subgridscale modeling. Turbulent mixing. Structure of low and high Reynolds number wall turbulence. Instructor: Dimotakis.

Ae 240. Special Topics in Fluid Mechanics. Units to be arranged; first, second, third terms. Subject matter changes depending upon staff and student interest. (1) Educational exchange at Ecole Polytechnique. Students participating in the Ecole Polytechnique educational exchange must register for 36 units while they are on detached duty at Ecole Polytechnique. For further information refer to the graduate option information for Aerospace. Instructor: McKeon.

Ae 241. Special Topics in Experimental Fluid and Solid Mechanics. Prerequisite: Ae/APh 104 or equivalent or instructor's permission. Units to be arranged; first, second, third terms. Subject matter changes depending upon staff and student interest.

Ae/BE 242. Biological Flows: Propulsion. 9 units (3-0-6); third 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. Not offered 2015-2016.

MedE/BE/Ae 243. Biological Flows: Transport and Circulatory Systems. 9 units (3-0-6); second term. For course description, see Medical Engineering.

Ae 244. Mechanics of Nanomaterials. 9 units (3-0-6); second 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. Not offered 2015–16.

Ae/CDS/ME 251 ab. Closed Loop Flow Control. 9 units; (3–0–6 a, 1–6–1– b); second, third term. Prerequisites: ACM 100abc, Ae/APh/CE/ME 101abc or equivalent. This course seeks to introduce students to recent developments in theoretical and practical aspects of applying control to flow phenomena and fluid systems. Lecture topics in the second term drawn from: the objectives of flow control; a review of relevant concepts from classical and modern control theory; high-fidelity and reduced-order modeling; principles and design of actuators and sensors. Third term: laboratory work in open- and closed-loop control of boundary layers, turbulence, aerodynamic forces, bluff body drag, combustion oscillations and flow-acoustic oscillations. Not offered 2015–16.

ME/Ge/Ae 266 ab. Dynamic Fracture and Frictional Faulting. 9 units (3–0–6). For course description, see Mechanical Engineering.

ANTHROPOLOGY

An 22. Introduction to Sociocultural Anthropology. 9 units (3–0–6); third term. 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); first 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. Instructor: Abrams.

An 97. Undergraduate Research. Units to be arranged; any term. Prerequisites: advanced Anthropology and instructor's permission.. This course offers advanced undergraduates the opportunity to pursue research in Anthropology individually or in a small group. Graded pass/fail.

An 101. Selected Topics in Anthropology. *Units to be determined by arrangement with the instructor; offered by announcement.* Topics to be determined by instructor. Instructor: Staff.

H/An 123. Anthropological Demography. *9 units (3-0-6); first term.* For course description, see History.

An/PS 127. Corruption. *9 units (3-0-6); third term. Prerequisites: AN 22 or PS 12.* Corruption taxes economies and individuals in both the developing and the developed world. We will examine what corruption means in different places and contexts, from grand financial scandals to misappropriation of development funds, ethnic patronage, and the theft of elections. How do we measure it? What are its costs and social consequences? What are its correlates? Does freedom of information matter? Students will read across a range of topics, and write an in-depth research paper on one topic. Limited enrollment. Instructor: Ensminger.

An 135. Primate Behavior. *9 units (3-0-6); third 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. Instructor: Staff. Not offered 2015–16.

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 2015–16.

An 150. The Caltech Project. *9 units (3-0-6), spring term. Prerequisites: An 22 or permission of instructor.* Hands-on immersion in a social scientific research project examining the Caltech undergraduate community. Core data collection includes a social network analysis and a rich array of socio-demographic data from the actual Caltech student body. Students will develop research design skills by writing and revising a 3000 word research proposal modeled on the NSF format. This unique data set allows us to address questions as diverse as: the impact of social networks upon academic performance, the origin and extent of socio-cultural differences across houses, and the diffusion of moral, political, academic, and religious values. Not offered 2015–16.

APPLIED AND COMPUTATIONAL MATHEMATICS

ACM 11. Introduction to Matlab and Mathematica. 6 units (2-2-2); *third term*. Prerequisites: *Ma 1 abc, 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. Instructors: Staff.

ACM 95/100 ab. Introductory Methods of Applied Mathematics for the Physical Sciences. 12 units (4-0-8); *second, third terms*. Prerequisites: *Ma 1 abc, Ma 2 or equivalents*. Complex analysis: analyticity, Laurent series, contour integration, residue calculus. Ordinary differential equations: linear initial value problems, linear boundary value problems, Sturm-Liouville theory, eigenfunction expansions, transform methods, Green's functions. Linear partial differential equations: heat equation, separation of variables, Laplace equation, transform methods, wave equation, method of characteristics, Green's functions. Instructors: Meiron, Pierce.

ACM 101 ab. Methods of Applied Mathematics. 12 units (4-0-8); *first, second, terms*. Prerequisites: *Math 2/102 and ACM 95ab*. First term: brief review of the elements of complex analysis and complex-variable methods. Asymptotic expansions, asymptotic evaluation of integrals (Laplace method, stationary phase, steepest descents), perturbation methods, WKB theory, boundary-layer theory, matched asymptotic expansions with first-order and high-order matching. Method of multiple scales for oscillatory systems. Second term: applied spectral theory, special functions, Hilbert spaces and linear operators, generalized eigenfunction expansions, convergence theory. Transform methods, distributions, Fourier Transform and Sobolev Spaces. Eigensystems and spectral theory for self-adjoint second order operators with variable coefficients in n -dimensional domains. Integral equations, Fredholm theorem, application to Laplace and Maxwell's equations, harmonicity at infinity, Kelvin transform, conditions of radiation at infinity. Instructor: Bruno.

CMS/ACM 104. Linear Algebra and Applied Operator Theory. 12 units (3-0-9); *first term*. For course description, see Computation and Mathematical Sciences.

ACM 105. Applied Real and Functional Analysis. 9 units (3-0-6); *second term*. Prerequisite: *ACM 100 ab 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: Tropp.

ACM 106 ab. Introductory Methods of Computational Mathematics. 12 units (3-0-9); second, third terms. Prerequisites: Ma 1 abc, Ma 2, Ma 3, ACM 11, ACM 95/100 ab 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 linear algebra parts covers basic methods such as direct and iterative solution of large linear systems, including LU decomposition, splitting method (Jacobi iteration, Gauss-Seidel iteration); eigenvalue and vector computations including the power method, QR iteration and Lanczos iteration; nonlinear algebraic solvers. The approximation theory includes data fitting; interpolation using Fourier transform, orthogonal polynomials and splines; least square method, and numerical quadrature. The ODE parts include initial and boundary value problems. The PDE parts include finite difference and finite element for elliptic/parabolic/hyperbolic equation. Stability analysis will be covered with numerical PDE. Programming is a significant part of the course. Instructor: Hou.

CMS/ACM 113. Mathematical Optimization. 9 units (3-0-6); first term. See course description in Computation and Mathematical Sciences.

ACM/CS 114 ab. Parallel Algorithms for Scientific Applications. 9 units (3-0-6); second, third 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 2015-16.

CMS/ACM 116. Introduction to Stochastic Processes and Modeling. 9 units (3-0-6); first term. For course description, see Computation and Mathematical Sciences.

AM/ACM 127. Calculus of Variations. 9 units (3–0–6) For course description, see Applied Mechanics.

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); second, third terms. For course description, see Mathematics.

ACM/EE 170. Mathematics of Signal Processing. 12 units (3–0–9); third term. Prerequisites: CMS/ACM 104, CMS/ACM 113, and CMS/ACM 116; or instructor's permission. This course covers classical and modern approaches to problems in signal processing. Problems may include denoising, deconvolution, spectral estimation, direction-of-arrival estimation, array processing, independent component analysis, system identification, filter design, and transform coding. Methods rely heavily on linear algebra, convex optimization, and stochastic modeling. In particular, the class will cover techniques based on least-squares and on sparse modeling. Throughout the course, a computational viewpoint will be emphasized. Not offered 2015–16.

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

ACM 201 ab. Partial Differential Equations. 12 units (4–0–8); first, second 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. Not offered 2015–16.

ACM 204. Topics in Convexity. 9 units (3–0–6); second term. Prerequisites: CMS/ACM 104 and CMS/ACM 113; or instructor's permission. The content of this course varies from year to year among advanced subjects in linear algebra, convex analysis, and related fields. Specific topics for the class include matrix analysis, operator theory, convex geometry, or convex algebraic geometry. Lectures and homework will require the ability to understand and produce mathematical proofs. Not offered 2015–16.

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. Not offered 2015–16.

ACM 213. Topics in Optimization. 9 units (3–0–6); third term. Prerequisites: CMS/ACM 104, CMS/ACM 113. Material varies year-to-year. Example topics include discrete optimization, convex and computational algebraic geometry, numerical methods for large-scale optimization, and convex geometry. Instructors: Chandrasekaran.

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: Owjadi.

ACM 217 ab. 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 2015–16.

ACM/CS/EE 218. Statistical Inference. 9 units (3–0–6); third term. Prerequisites: CMS/ACM 104 and CMS/ACM/EE 116, or instructor's permission.

Fundamentals of estimation theory and hypothesis testing; Bayesian and non-Bayesian approaches; minimax analysis, Cramer-Rao bounds, shrinkage in high dimensions; Kalman filtering, basics of graphical models; statistical model selection. Throughout the course, a computational viewpoint will be emphasized. Not offered 2015–16.

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); first term. 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 2015–16.

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 2015–16.

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

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 ab. Computational Mechanics. 9 units (3-0-6). For course description, see Civil Engineering.

AM/ACM 127. Calculus of Variations. 9 units (3-0-6); third term. Prerequisites: ACM 95/100. First and second variations; Euler-Lagrange equation; Hamiltonian formalism; action principle; Hamilton-Jacobi theory; stability; local and global minima; direct methods and relaxation; isoperimetric inequality; asymptotic methods and gamma convergence; selected applications to mechanics, materials science, control theory and numerical methods. Not offered 2015-16.

AM/CE/ME 150 abc. Graduate Engineering Seminar. 1 unit; each term; first, second and third terms. Students attend a graduate seminar each week of each term and submit a report about the attended seminars. At least four of the attended seminars each term should be from the Mechanical and Civil Engineering seminar series. Students not registered for the M.S. and Ph.D. degrees must receive the instructor's permission. Graded pass/fail. Instructor: Staff.

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, Asimaki.

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 2015-16.

AM 200. Advanced Work in Applied Mechanics. Hours and units by arrangement. A faculty mentor will oversee a student proposed, independent research or study project to meet the needs of graduate students. Graded pass/fail. The consent of a faculty mentor and a written report is required for each term of work.

AM 201. Advanced Topics in Applied Mechanics. 9 units (3-0-6). The faculty will prepare courses on advanced topics to meet the needs of graduate students.

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

APPLIED PHYSICS

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, third 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. Not offered 2015–2016. Aph majors are required to take Ph 12 instead.

Aph 23. Demonstration Lectures in Optics. 6 units (2-0-4); second term. Prerequisites: 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, adaptive optical systems and nano-photonic devices. Instructor: Faraon.

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: Faraon.

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, open only to senior-class applied physics majors. Requirements will be set by individual faculty member, but must include a written report. The selection of topic must be approved by the Applied Physics Option Representative. Not offered on a pass/fail basis. Final grade based on written thesis and oral exam. Instructor: Staff.

APh 79 abc. Senior Thesis, Theoretical. 9 units (0-9-0); first, second, third terms. *Prerequisite:* instructor's permission. Supervised theoretical research, open only to senior-class applied physics majors. Requirements will be set by individual faculty member, but must include a written report. The selection of topic must be approved by the Applied Physics Option Representative. Not offered on a pass/fail basis. Final grade based on written thesis and oral exam. 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/MS 105 abc. States of Matter. 9 units (3-0-6); first, second, third terms. Prerequisites: APh 17 abc or equivalent. Thermodynamics and statistical mechanics, with emphasis on gases, liquids, materials, and condensed matter. Effects of heat, pressure, and fields on states of matter are presented with both classical thermodynamics and with statistical mechanics. Conditions of equilibrium in systems with multiple degrees of freedom. Applications include ordered states of matter and phase transitions. The three terms cover, approximately, thermodynamics, statistical mechanics, and phase transitions. 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: Painter, 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. Instructors: Painter, 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: Atwater, Schwab.

APh/Ph 115. Physics of Momentum Transport in Hydrodynamic Systems. 12 units (3-0-9); second term. Prerequisites: ACM 95 or equivalent. Contemporary research in many areas of physics requires some knowledge of the principles governing hydrodynamic phenomena such as nonlinear wave propagation, symmetry breaking in pattern forming systems, phase transitions in fluids, Langevin dynamics, micro- and optofluidic control, and biological transport at low Reynolds number. This course offers students of pure and applied physics a self-contained treatment of the fundamentals of momentum transport in hydrodynamic systems. Mathematical techniques will include formalized dimensional analysis and rescaling, asymptotic analysis to identify dominant force balances, similitude, self-similarity and perturbation analysis for examining unidirectional and Stokes flow, pulsatile flows, capillary phenomena, spreading films, oscillatory flows, and linearly unstable flows leading to pattern formation. Students must have working knowledge of vector calculus, ODEs, PDEs, complex variables and basic tensor analysis. Advanced solution methods will be taught in class as needed. Second term is APh/Ph/Ae 116. Instructor: Troian.

APh/Ph/Ac 116. Physics of Thermal and Mass Transport in Hydrodynamic Systems. 12 units (3-0-9); first term. Prerequisites: ACM 95 or equivalent and APh/Ph 115 or equivalent. Contemporary research in many areas of physics requires some knowledge of how momentum transport in fluids couples to diffusive phenomena driven by thermal or concentration gradients. This course will first examine processes driven purely by diffusion and progress toward description of systems governed by steady and unsteady convection-diffusion and reaction-diffusion. Topics will include Fickian dynamics, thermal transfer in Peltier devices, Lifshitz-Slyozov growth during phase separation, thermocouple measurements of oscillatory fields, reaction-diffusion phenomena in biophysical systems, buoyancy driven flows, and boundary layer formation. Students must have working knowledge of vector calculus, ODEs, PDEs, complex variables and basic tensor analysis. Advanced solution methods such as singular perturbation, Sturm-Liouville and Green's function analysis will be taught in class as needed. First term is APh/Ph 115. Instructor: Troian.

Ph/APh/EE/BE 118 ab. Physics of Measurement. 9 units (3-0-6); first and second terms. For course description, see Physics.

Ph/APh/EE/BE 118 c. Physics of Measurement. 9 units (3-0-6); third terms. For course description, see Physics.

MS 132. Diffraction and Structure. 9 units (3-0-6). For course description, see Materials Science.

MS/APh 122. Diffraction, Imaging, and Structure. 9 units (0-4-5); second and third terms. For course description, see Materials Science.

APh/EE 130. Electromagnetic Theory. 9 units (3-0-6); first term. Electromagnetic fields in vacuum: microscopic Maxwell's equations. Monochromatic fields: Rayleigh diffraction formulae, Huygens principle, Rayleigh-Sommerfeld formula. The Fresnel-Fraunhofer approximation. Electromagnetic field in the presence of matter, spatial averages, macroscopic Maxwell equations. Helmholtz's equation. Group-velocity and group-velocity dispersion. Confined propagation, optical resonators, optical waveguides. Single mode and multimode waveguides. Nonlinear optics. Nonlinear propagation. Second harmonic generation. Parametric amplification. Instructor: Crosignani.

EE/APh 131. Light Interaction with Atomic Systems - Lasers. 9 units (3-0-6); second term. Prerequisites: APh/EE 130. For course description, see Electrical Engineering.

APh/EE 132. Special Topics in Photonics and Optoelectronics. 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. Not offered 2015-2016.

APh 150. Topics in Applied Physics. *Units to be arranged; first term.*

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. Instructor: Painter.

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 (magneto-sphere, solar) will be discussed. Instructor: Bellan.

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

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

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: Vahala, 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 ab. Advanced Condensed-Matter Physics. *9 units (3-0-6); second, third terms.* 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

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 2015–16.

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 2015–16.

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 2015–16.

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 2015–16.

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. Not offered 2015–16.

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); *third 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. Not offered 2015–16.

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 2015–16.

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 2015–16.

Art/H 68. Modern Art. *9 units (3-0-6); first term.* The purpose of this course is to give students a broad view of the history and significance of Western art in the 19th and 20th centuries. We will focus on the impact that shifts in production and social relations—generally referred to as “modernization”—had on culture from 1850–1950. Through close readings of primary and secondary texts, we will unpack some of the modernist period’s most influential developments, such as the relation between industrial and cultural production, the seeming contest between mass and avant-garde culture, and utopian cultural theories. The course aims to provide students with an understanding and appreciation of the history of modernist art in the West, as well as the tools with which to write about visual culture analytically. Not offered 2015–16.

Art/H 69. Modernism in the Visual Arts, 1850–1945. *9 units (3-0-6); second term.* This course examines European and American painting, sculpture, photography, and other visual arts from 1850 to the mid-twentieth century. An era encompassing many diverse and significant developments in modern art, this period includes Impressionism, Post-Impressionism, Symbolism, Expressionism, Cubism, Dada, Surrealism, and Abstract Expressionism. Artworks from these movements will be studied in light of their social, cultural, and political contexts, with particular attention paid to issues of gender and representation, and to the different forms of abstraction developed and theorized by early twentieth-century painters. The class will also focus on the relationships of colonialism, urbanism, rising industrialism, and international conflict to the visual culture of the period. Not offered 2015–16.

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. Not offered 2015–15.

Art 71. Arts of Buddhism. *9 units (3-0-6); second 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.

E/H/Art 89. New Media Arts in the 20th and 21st Centuries. *9 units (3-0-6).* For course description, see Engineering.

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

Art/H 153. The Politics of Representation in American Art, 1935-2000. 9 units (3-0-6); *first term*. This course examines major historical concerns and artistic themes in American Art from 1935, the advent of the Popular Front, to the end of the 20th century, the heart of post-modernism. We shall read art historical and theoretical texts so as to understand the role of art in the formation of American identity. In addition to familiarizing students with a broad range of themes within the history of American art, this course will analyze the relation between art and broader social and political contexts. Not offered 2015-15.

Art/H 154. Art and Technology. 9 units (3-0-6); *third term*. From perceptual experiments in abstract art to hacktivism and neuroaesthetics, this course explores interactions and interventions between art and technology from the 1960s to the present. Our focus will be on artists and artists groups working in the last forty years who have taken developments in science and technology as their primary subject of inquiry and critique. Topics include experiments in perceptual technology, land use, scientific representations, bio-art, net.art and data use. Students will engage in a research project that focuses on a recent collaboration between art and science. Not offered 2015-16.

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 2015-16.

Art 169. The Arts of Dynastic China. 9 units (3-0-6); *first term*. A survey of the development of Chinese art in which the major achievements in architecture, sculpture, painting, calligraphy, and ceramics will be studied in their cultural contexts from prehistory through the Manchu domination of the Qing Dynasty (1644-1911). Emphasis will be placed on the aesthetic appreciation of Chinese art as molded by the philosophies, religions, and history of China. Instructor: Wolfgram.

Art/H 183. Spectacle: From the Court Masque to the Great Exhibition of 1851. 9 units (3-0-6); *first 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. Not offered 2015–16.

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 Big Bang cosmology. This class will be offered in a “flipped classroom” mode: the students will be required to watch the video lectures first, and then discuss them and work out problems in the classroom. A field trip to Palomar Observatory will be organized. Not offered on a pass/fail basis. Instructor: Djorgovski.

FS/Ay 3. Freshman Seminar: Automating Discovering the Universe. 6 units (2–0–4); second term. For course description, see Freshman Seminar.

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 or instructor's permission.* The electromagnetic spectrum and basic radiative transfer; ground and space observing techniques; “pictorial Fourier description” of astrophysical optics; Kepler’s laws; exoplanets; stellar masses, distances, and motions; the birth, structure, evolution, and death of stars; the structure and dynamics of the Galaxy. Lessons will emphasize the use of order-of-magnitude calculations and scaling arguments in order to elucidate the physics of astrophysical phenomena. Short labs will introduce astronomical measurement techniques. Instructor: Hillenbrand.

Ay 21. Galaxies and Cosmology. 9 units (3–0–6); second term. *Prerequisites: Ma 1 abc, Ph 1 abc or instructor's permission.* 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: Djorgovski

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: Cohen.

Ay 31. Writing in Astronomy. 3 units (1-0-2); 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 most suitable for juniors and seniors. Fulfills the Institute scientific writing requirement. Instructor: Hillenbrand.

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. Instructor: Staff.

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. Previous SURF or independent study work can be useful experience. Course is open to senior astronomy majors only. Research must be supervised by a faculty member. Students wishing assistance in finding an adviser and/or a topic for a senior thesis are invited to consult with the astronomy option representative. The student will work with an advisor to formulate a research project, conduct original research, present new results, and evaluate them in the context of previously published work in the field. The first two terms are graded pass/fail and the grades are then changed at the end of the course to the appropriate letter grade for all three terms. In order to receive a passing grade for second term, a work plan and a preliminary thesis outline must be submitted. The written thesis of 20–100 pages must be completed and approved by the adviser and the option representative before the end of the third term. Instructor: Staff.

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: Cohen.

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: Kulkarni.

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 consequences: (neutron stars) pulsars, magnetars, X-ray binaries, gamma-ray bursts; (black holes) X-ray transients, tidal disruption and quasars/active galaxies and sources of gravitational waves. Instructor: Kasliwal.

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

Ay 111 a. Introduction to Current Astrophysics Research. 3 units; first term. 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 astronomy 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. Instructor: Hallinan.

Ge/Ay 117. Statistics and Data Analysis. 9 units (3-0-6); third term. *Prerequisites:* CS 1 and instructor's permission. For course description, see Geological and Planetary Sciences.

Ay 119. Methods of Computational Science. 9 units (3-0-6); third term. Open to graduate and upper-division undergraduate students in all options. Practical computational science methods useful in disciplines dealing with large and/or complex data sets. Topics include: 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. Instructor: Djorgovski.

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, coherent emission processes, synchrotron radiation, collisional excitation, spectroscopy of atoms and molecules. Instructors: Hallinan, Kirby.

Ay 122 abc. Astronomical Measurements and Instrumentation. 9 units (3-0-6); in 2015-16, only 122 a is offered, first term. Prerequisite: Ph 106 or equivalent. Telescopes, optics, detectors, radiometers, photometry, spectroscopy. Active/adaptive optics. Interferometers/arrays. Imaging devices and image processing. Antennae, receivers, mixers, and amplifiers. Space telescopes. Signal analysis techniques and probability and statistics as relevant to astronomical measurement. Some lab work and observatory field trips. Ay 122 a concentrates on infrared, optical, and ultraviolet techniques. Ay 122 b (not offered 2015-16) concentrates on radio through submillimeter techniques, and Ay 122 c (not offered 2015-16) concentrates on X-ray through gamma-ray techniques. Instructors: (a) Steidel, Mawet.

Ay 123. Structure and Evolution of Stars. 9 units (3-0-6); second 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: Kirby.

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. Instructor: Steidel.

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

Ay 126. Interstellar and Intergalactic 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. Instructor: Hopkins.

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. Instructor: Hopkins.

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); *second term*. 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. (a) Hopkins, Kirby; (b) Cohen, Mawet; (c) Kasliwal, Phinney.

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 for graduate students. 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 for graduate students. 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. Not offered 2015-16.

Ay/Ge 198. Special Topics in the Planetary Sciences. 9 units (3-0-6); *third term*. Topic for 2015-16 is Extrasolar Planets. Thousands of planets have been identified in orbit around other stars. Astronomers are now embarking on understanding the statistics of extrasolar planet populations and characterizing individual systems in detail, namely star-planet, planet-planet and planet-disk dynamical interactions, physical parameters of planets and their composition, weather phenomena, etc. Direct and indirect detection

techniques are now completing the big picture of extra-solar planetary systems in all of their natural diversity. The seminar-style course will review the state of the art in exoplanet science, take up case studies, detail current and future instrument needs, and anticipate findings. Instructors: Batygin, Hillenbrand, Mawet.

Ay 211. Contemporary Extragalactic Astronomy. 9 units (3-0-6); *third term*. Prerequisites: Ay 123, Ay 124, and Ay 127. 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 2015–2016.

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 2015–16.

Ay 218. Extrasolar Planets. 9 units (3-0-6); *third term*. Extrasolar Planets. For 2015–16, this course is being offered as Ay/Ge 198.

Ay 219. Elements in the Universe and Galactic Chemical Evolution. 9 units (3-0-6); *second 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 stars, meteorites, H II regions, and in interstellar and intergalactic gas. Overview of models of galactic chemical evolution. Participants will measure elemental abundances from the Keck spectrum of a star and construct their own numerical chemical evolution models. Not offered 2015–16.

BIOCHEMISTRY AND MOLECULAR BIOPHYSICS

BMB/Bi/Ch 170. Biochemistry and Biophysics of Macromolecules and Molecular Assemblies. 9 units (3-0-6); *first*. Prerequisites: Bi/Ch 110. 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. Instructors: Clemons.

BMB/Bi/Ch 173. Biophysical/Structural Methods. 9 units (3-0-6); *second*. Basic principles of modern biophysical and structural methods used to interrogate macromolecules from the atomic to cellular levels, including light and electron microscopy, X-ray crystallography, NMR spectroscopy, single molecule techniques, circular dichroism, surface plasmon resonance, mass spectrometry, and molecular dynamics and systems biological simulations. Instructors: Clemons, Grant, and other guest lecturers

BMB/Bi/Ch 174. Molecular Machines in the Cell. 9 units (3-0-6); *third*. Prerequisites: Bi/Ch 110, BMB/Bi/Ch 170, BMB/Bi/Ch 173. Detailed

analysis of specific macromolecular machines and systems that illustrate the principles and biophysical methods taught in BMB/Bi/Ch 170 and BMB/Bi/Ch 173. Instructors: Shan, Hoelz and various guest lecturers (subject to change each year).

BMB/Ch 178. Macromolecular Function: Kinetics, Energetics, and Mechanisms. 9 units (3–0–6); first term. *Prerequisites:* Bi/Ch 110 or equivalent. Discussion of the energetic principles and molecular mechanisms that underlie enzyme's catalytic proficiency and exquisite specificity. Principles of allosteric regulation, selectivity, enzyme evolution, and computational enzyme design. Practical kinetics sections discuss how to infer molecular mechanisms from rate/equilibrium measurements and their application to more complex biological systems, including steady-state and pre-steady-state kinetics, kinetic simulations, and kinetics at the single molecule resolution. Instructors: 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. Students will meet with the Biochemistry seminar speaker in the discussion section for an hour, and then attend the Biochemistry seminar at 4 p.m. BMB Seminars take place 1–2 times per month (usually on Thursdays).

BMB/Ch 230. Macromolecular Structure Determination with Modern X-ray Crystallography Methods. 12 units (2–4–6); third term. *Prerequisites:* BMB/Bi/Ch 170 and consent of instructor. Advanced course in macromolecular crystallography integrating lecture and laboratory treatment of diffraction theory, crystallization (proteins, nucleic acids and macromolecular complexes), crystal characterization, X-ray sources and optics, crystal freezing, X-ray diffraction data collection (in-house and synchrotron), data reduction, multiple isomorphous replacement, single- and multi-wavelength anomalous diffraction phasing techniques, molecular replacement, electron density interpretation, structure refinement, structure validation, coordinate deposition and structure presentation. In the laboratory component, one or more proteins will be crystallized and the structure(s) determined by several methods, in parallel with lectures on the theory and discussions of the techniques. Instructors: Hoelz.

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 2015–16.

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. Required for BE undergraduates. Graded pass/fail. Instructor: Staff.

Bi/BE 24. Technical Communication for Biological Scientists and Engineers. *6 units (3-0-3); first, third terms.* For course description, see Biology.

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/Bi 101. Order of Magnitude Biology. *6 units (3-0-3); third term.* *Prerequisites: none.* In this course, students will develop skills in the art of educated guesswork and apply them to the biological sciences. Building from a few key numbers in biology, students will “size up” biological systems by making inferences and generating hypotheses about phenomena such as the rates and energy budgets of key biological processes. The course will cover the breadth of biological scales: molecular, cellular, organismal, communal, and planetary. Undergraduate and graduate students of all levels are welcome. Instructors: Bois, Phillips. Offered alternate years; offered 2015–16.

BE/Bi 103. Data Analysis in the Biological Sciences. *9 units (1-3-5); first term.* *Prerequisites: CS 1 or equivalent; Bi 1, Bi 1x, Bi 8, or equivalent; or instructor's permission.* This course covers a basic set of tools needed to analyze quantitative data in biological systems, both natural and engineered. Students will analyze real data in class and in homework. Python will be used as the programming language of instruction. Topics will include regression, parameter estimation, outlier detection and correction, error estimation, image processing and quantification, denoising, hypothesis testing, and data display and presentation. Instructor: Bois.

BE/Bi/MedE 106. 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 2015–16.

BE 107. Exploring Biological Principles Through Bio-Inspired Design. *9 units (3-5-1); third term.* *Prerequisites: None.* Students will formulate and implement an engineering project designed to explore a biological principle or property that is exhibited in nature. Students will work in small teams

in which they build a hardware platform that is motivated by a biological example in which a given approach or architecture is used to implement a given behavior. Alternatively, the team will construct new experimental instruments in order to test for the presence of an engineering principle in a biological system. Example topics include bio-inspired control of motion (from bacteria to insects), processing of sensory information (molecules to neurons), and robustness/fault-tolerance. Each project will involve proposing a specific mechanism to be explored, designing an engineering system that can be used to demonstrate and evaluate the mechanism, and building a computer-controlled, electro-mechanical system in the lab that implements or characterizes the proposed mechanism, behavior or architecture. Instructors: Dickinson, Murray.

ChE/BE/MedE 112. Design, Invention, and Fundamentals of Microfluidic Systems. 9 units (3-0-6); second term. For course description, see Chemical Engineering.

Ph/APh/EE/BE 118 ab. Physics of Measurement. 9 units (3-0-6); first and second terms. For course description, see Physics.

Ph/APh/EE/BE 118 c. Physics of Measurement. 9 units (3-0-6); third terms. For course description, see Physics.

BE 150. Design Principles of Genetic Circuits. 9 units (3-0-6); third term. *Prerequisites: none.* Quantitative studies of cellular and developmental systems in biology, including the architecture of specific genetic circuits controlling microbial behaviors and multicellular development in model organisms. Specific topics include chemotaxis, multistability and differentiation, biological oscillations, stochastic effects in circuit operation, as well as higher-level circuit properties such as robustness. Organization of transcriptional and protein-protein interaction networks at the genomic scale. Topics are approached from experimental, theoretical and computational perspectives. Instructors: Bois, Elowitz.

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.

Bi/NB/BE 155. Neuropharmacology. 6 units (3-0-3); second term. For course description, see Biology.

BE 159. Signal Transduction and Mechanics in Morphogenesis. 9 units (3-0-6); second term. *Prerequisites: Bi 8, Bi 9, ACM 95 ab, or instructor's permission.* This course examines the mechanical and biochemical pathways that govern morphogenesis. Topics include embryonic patterning, cell polarization, cell-cell communication, and cell migration in tissue develop-

ment and regeneration. The course emphasizes the interplay between mechanical and biochemical pathways in morphogenesis. Instructor: Bois.

BE/Aph 161. Physical Biology of the Cell. 12 units (3-0-9); second term. *Prerequisites:* Ph 2ab and ACM 95abc, or background in differential equations and statistical and quantum mechanics, or instructor's written permission. 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: Bois.

ChE/BE 163. Introduction to Biomolecular Engineering. 12 units (3-0-9); first term. For course description, see Chemical Engineering.

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

BE 167. Research Topics in Bioengineering. 1 unit; first term. Introduction to current research topics in Caltech bioengineering labs. Graded pass/fail. Instructor: Staff.

BE 168. Reading the Bioengineering Literature. 4 units (1-0-3); second term. *Prerequisites:* None. Participants will read, discuss, and critique papers on diverse topics within the bioengineering literature. *Enrollment limited to 10 students; undergraduates with instructor's permission.* Instructor: Winfree. Offered in alternate years; not offered 2015-16.

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

Bi/BE 182. Animal Development and Genomic Regulatory Network Design. 9 units (3-0-6); second term. For course description, see Biology.

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

ChE/BE/MedE 188. Molecular Imaging. 9 units (3-0-6); second term. For course description see Chemical Engineering.

BE/EE/MedE 189 ab. Design and Construction of Biodevices. 12 units (3-6-3) a = first and second terms; 9 units (0-9-0) b = second term. *Prerequisites:* ACM 95 ab (for BE/EE/MedE 189 a); BE/EE/MedE 189 a (for BE/EE/MedE 189 b). Part a, 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. Part b is a student-initiated design project requiring instructor's permission for enrollment. Enrollment is limited to 24 students. BE/EE/MedE 189 a is an option requirement; BE/EE/MedE 189 b is not. Instructor: Yang.

BE/CS/CNS/Bi 191 ab. Biomolecular Computation. 9 units (3-0-6) second term; (2-4-3) third term. *Prerequisite:* none. *Recommended:* ChE/BE 163, 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/CS 196 ab. Design and Construction of Programmable Molecular Systems. a = 12 units (3-6-3) second term; b = 12 units (2-8-2) third term. *Prerequisites:* ChE/BE 163 or BE/CS/CNS/Bi 191a, or instructor's permission. This course will introduce students to the conceptual frameworks and tools of computer science as applied to molecular engineering, as well as to the practical realities of synthesizing and testing their designs in the laboratory. In part a, students will design and construct DNA logic circuits, biomolecular neural networks, and complex two-dimensional and three-dimensional nanostructures, as well as quantitatively analyze the designs and the experimental data. Students will learn laboratory techniques including gel electrophoresis, fluorescence spectroscopy, and atomic force microscopy, and will use software tools and program in Mathematica or Mat lab. Part b is an open-ended, design-and-build project requiring instructor's permission for enrollment. Enrollment in both parts a and b is limited to 12 students. Instructor: Qian.

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.

BE/Bi/NB 203. Introduction to Programming for the Biological Sciences Bootcamp. 6 units; summer. *Prerequisites:* none. This course provides an intensive, hands-on, pragmatic introduction to computer programming aimed at biologists and bioengineers. No previous programming experience is assumed. Python is the language of instruction. Students will learn basic concepts such as data types, control structures, string processing, functions, input/output, etc., while writing code applied to biological problems. At the end of the course, students will be able to perform simple simulations, write scripts to run software packages and parse output, and analyze and plot data. This class is offered as a week long "boot camp," starting two weeks before the start of the fall term, in which students spend all day working on the course. Graded pass/fail. Instructors: Bois, Guttman.

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

Bi/CNS/BE/NB 230. Optogenetic and CLARITY Methods in Experimental Neuroscience. 9 units (3-2-4); third term. 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.

MedE/BE/Ae 243. Biological Flows: Transport and Circulatory Systems. 9 units (3-0-6); second term. For course description, see Medical Engineering.

BIOLOGY

Bi 1. Principles of Biology. 9 units (4-0-5); third term. Advances in biotechnology have driven unprecedented integration across the hierarchy of biology, from molecules to ecosystems, as well as the integration of biology with other sciences, including geology, physics, chemistry and mathematics. The design of this biology course seeks to provide introductory students with a strong foundation built on a set of basic principles that will provide students with the intellectual tools for critical thinking in the discipline. Because the microbial world has been critical in all aspects of biology, from the environmental to human health, throughout the evolution of the biosphere, a microbiological perspective will form the nucleus around which each major topic will be developed. Specifically, we will discuss key concepts in cellular and molecular biology (e.g. cytoskeletal elements, transcription, translation), ecology, evolution, and metabolism (e.g. biosynthesis and energy generation) by providing examples from the microbial world. Instructor: Newman.

Bi 1 x. The Great Ideas of Biology: Exploration 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: Bois.

Bi 2. Current Research in Biology. 3 units (1-0-2); 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 (4-0-5); second term.

This course and its sequel, Bi 9, cover biology at the molecular and cellular levels. Bi 8 emphasizes genomic structure and mechanisms involved in the organization and regulated expression of genetic information. The focus is on the ways that the information content of the genome is translated into distinctive, cell type specific patterns of gene expression and protein function, with special attention to the problems of gene regulation in complex multicellular organisms. Assignments will include critical dissections of papers from current research literature and individual oral presentations by students to the class on specific topics. 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. Introductory Biology Laboratory. 6 units (1-3-2); third term. *Prerequisites: Bi 8; designed to be taken concurrently with Bi 9.* An introduction to molecular, cellular, and biochemical techniques that are commonly used in studies of biological systems at the molecular level. Instructor: Staff.

FS/Bi 13. In Search of Memory. 6 units (2-0-4). For course description, see Freshman Seminar.

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 Tutorials. 3 or 6 units; second term. Small group study and discussion in depth of special areas or problems in biology, involving regular tutorial sections with instructors drawn from the divisional postdoctoral staff and others. Usually given winter term. To be arranged with instructors before registration. Graded pass/fail. Instructor: Huang.

Bi/BE 24. Technical Communication for Biological Scientists and Engineers. 6 units (3-0-3); first, third terms. This course offers instruction and practice in writing and speaking relevant to professional biological scientists and engineers working in research, teaching, and/or medical careers. Students will write a paper for a scientific or engineering journal, either based on their previous research or written as a review paper of current work in their field. 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 paper. Oral presentations will be based on writing produced in the course, with feedback from instructors and peers. Fulfills the Institute scientific writing requirement. Instructor: Staff.

Bi 90 abc. Undergraduate Thesis. 12 or more units per term; first, second, third terms. *Prerequisites: 18 units of Bi 22 (or equivalent research experience) in the research area proposed for the thesis, and instructor's permission.* Intended

to extend opportunities for research provided by Bi 22 into a coherent individual research project, carried out under the supervision of a member of the biology faculty. Normally involves three or more consecutive terms of work in the junior and senior years. The student will formulate a research problem based in part on work already carried out, evaluate previously published work in the field, and present new results in a thesis format. First two terms graded pass/fail; final term graded by letter on the basis of the completed thesis. Instructor: Bjorkman.

BE/Bi 101. Order of Magnitude Biology. 6 units (3-0-3); second term. For course description, see Bioengineering.

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

BE/Bi 103. Data Analysis in the Biological Sciences. 9 units (1-3-5); first term. For course description, see Bioengineering.

Bi/Ge/ESE 105. Evolution. 12 units (3-4-5); second term. *Prerequisites: Completion of Core Curriculum Courses. Maximum enrollment: 15, by application only.* The theory of evolution is arguably biology's greatest idea and serves as the overarching framework for thinking about the diversity and relationships between organisms. This course will present a broad picture of evolution starting with discussions of the insights of the great naturalists, the study of the genetic basis of variation, and an introduction to the key driving forces of evolution. Following these foundations, we will then focus on a number of case studies including the following: evolution of oxygenic photosynthesis, origin of eukaryotes, multicellularity, influence of symbiosis, the emergence of life from the water (i.e. fins to limbs), the return of life to the water (i.e. limbs to fins), diversity following major extinction events, the discovery of Archaea, insights into evolution that have emerged from sequence analysis, and finally human evolution and the impact of humans on evolution (including examples such as antibiotic resistance). A specific focus for considering these issues will be the island biogeography of the Galapagos. Instructors: Phillips, Orphan. Given in alternate years; offered 2015-16.

BE/Bi/MedE 106. Introduction to Biomechanics. 9 units (3-0-6); third term. 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. Instructor: Biochemistry faculty.

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 or consent of instructor. Lectures and recitation on the biochemistry of basic cellular processes in the cytosol and organelles, with emphasis on membrane and protein trafficking. Specific topics include protein secretion, virus entry, endocytosis, endoplasmic reticulum dynamics, nuclear trafficking, autophagy, apoptosis, and mitochondrial dynamics. The relationship of these processes to human disease will be discussed. Instructors: Chan, Hoelz.

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, gene rearrangement of lymphocyte receptors, cytokines and the regulation of cellular responses, T and B cell development, and mechanisms of tolerance. The course will present an integrated view of how the immune system interacts with viral and bacterial pathogens and commensal bacteria. Instructors: Mazmanian, Bjorkman.

Bi 115. Attack and Repulsion: Viruses and their Hosts. 9 units (3–0–6); third 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; offered 2015–16.

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.

Bi 118. Morphogenesis of Developmental Systems. 6 units (2–0–4); first term. Prerequisites: Bi 8 and Bi 9, and at least one of the following: Bi 117, Bi 122, Bi 129, Bi 145, or Bi/BE 182 (or equivalents). Discussion of how cells, tissues, and organs take shape: the influence of force on cell shape change; cell migration including chemotaxis and collective cell movement; adhe-

sion/deadhesion during migration; the relationship between cell migration and metastasis; and a review/overview of general signaling principles and embryonic development of invertebrate and vertebrate animals. Class size is limited to 5 students. Given in alternate years; not offered 2015–16.

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 129. Biology of Cancer. 9 units (3–0–6); second 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. Given in alternate years; not offered 2015–16.

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, Cai.

Bi 145 a. Tissue and Organ Physiology. 9 units (3–0–6); first term. Prerequisites: Bi 8, 9, 110. Bi 110 may be taken concurrently. Reviews of anatomy and histology, as well as in-depth discussion of cellular physiology. Building from cell function to tissues, the course explores human physiology in an organ-based fashion. First term topics include endocrine physiology, the skeletal system, digestive and hepatic physiology, nutrition and urinary physiology. Particular emphasis is placed on health issues and pharmaceutical therapy from both a research and a medical perspective. Instructor: Tydell.

Bi 145 b. Tissue and Organ Physiology. 9 units (3–0–6); second term. Prerequisites: Bi 145a. Building on the foundations of Bi 145a, Bi 145b will continue the exploration of human physiology incorporating anatomy and cellular physiology. Topics include muscle physiology, cardiovascular physiology, the respiratory system and reproductive physiology. Particular emphasis is placed on health issues and pharmaceutical therapy from both a research and a medical perspective. Instructor: Tydell.

Bi/CNS/NB 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/CNS/NB 153. Brain Circuits. 9 units (3-0-6); first term. Prerequisites: Bi/CNS/NB 150 or equivalent. What functions arise when many thousands of neurons combine in a densely connected circuit? Though the operations of neural circuits lie at the very heart of brain science, our textbooks have little to say on the topic. Through an alternation of lecture and discussion this course explores the empirical observations in this field and the analytical approaches needed to make sense of them. We begin with a foray into sensory and motor systems, consider what basic functions they need to accomplish, and examine what neural circuits are involved. Next we explore whether the circuit motifs encountered are also found in central brain areas, with an emphasis on sensory-motor integration and learning. Finally we discuss design principles for neural circuits and what constraints have shaped their structure and function in the course of evolution. Given in alternate years; not offered 2015-16.

Bi/NB/BE 155. Neuropharmacology. 6 units (3-0-3); second term. Prerequisites: Bi/CNS/NB 150. The neuroscience of drugs for therapy, for prevention, and for recreation. Students learn the prospects for new generations of medications in neurology, psychiatry, aging, and treatment of substance abuse. Topics: Types of drug molecules. Drug receptors. Electrophysiology. Drugs activate ion channels. Drugs block ion channels. Drugs activate and block G protein pathways. Drugs block neurotransmitter transporters. Pharmacokinetics. Recreational drugs. Nicotine Addiction. Opiate Addiction. Drugs for neurodegenerative diseases: Alzheimer's disease, Parkinson's disease. Drugs for epilepsy and migraine. Psychiatric diseases: nosology and drugs. The course is taught at the research level. Given in alternate years, not offered 2015-16.

Bi/NB 156. Molecular Basis of Behavior. 9 units (3-0-6); second term. Prerequisite: Bi/CNS/NB 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. Given in alternate years; not offered 2015-16.

Bi/CNS/NB 157. Comparative Nervous Systems. 9 units (2-3-4); third term. Prerequisites: instructor's permission. 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. Letter grades only. Given in alternate years; not offered 2015-16.

Bi/CNS 158. Vertebrate Evolution. 9 units (3-0-6); third term. Prerequisites: Bi 1, Bi 8, or instructor's permission. 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. Letter grades only. Instructor: Allman. Given in alternate years; offered 2015–16.

Bi/CNS/NB 162. Cellular and Systems Neuroscience Laboratory.

12 units (2–7–3); third term. Prerequisites: Bi/CNS/NB 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: Staff.

Bi/CNS/NB 164. Tools of Neurobiology. *9 units (3–0–6); second term. Prerequisites: Bi/CNS/NB 150 or equivalent.* Offers a broad survey of methods and approaches to understanding in modern neurobiology. The focus is on understanding the tools of the discipline, and their use will be illustrated with current research results. Topics include: molecular genetics, disease models, transgenic and knock-in technology, virus tools, tracing methods, gene profiling, light and electron microscopy, optogenetics, optical and electrical recording, neural coding, quantitative behavior, modeling and theory. Instructor: Meister.

Bi 165. Microbiology Research: Practice and Proposal. *6 units (2–3–1); first term; Enrollment limited to instructor approval.* The course will serve to introduce graduate students to 1) ongoing research projects on campus involving the isolation, culture, and characterization of microbes and microbial communities; and 2) the process of writing fellowships having a microbiology focus to train students in preparing effective funding applications. The first phase will involve a series of research presentations by different laboratory groups over the course of three evenings for one week at the start of the course. The second phase over the term will involve training in grant writing by drafting an NSF-type proposal, and a final oral presentation of the students' proposals. Not offered 2015–16.

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. Biochemistry and Biophysics of Macromolecules and Molecular Assemblies. *9 units (3–0–6); first.* For course description, see Biochemistry and Molecular Biophysics.

BMB/Bi/Ch 173. Biophysical/Structural Methods. 9 units (3-0-6); *second*. For course description, see Biochemistry and Molecular Biophysics.

BMB/Bi/Ch 174. Molecular Machines in the Cell. 9 units (3-0-6); *third*. For course description, see Biochemistry and Molecular Biophysics.

CNS/Bi/SS/Psy/NB 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); *second 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 and characteristics of lenses and microscopes. 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 and the analysis and presentation of two- and three-dimensional images. The role of light microscopy in the history of science will be an underlying theme. No prior knowledge of microscopy will be assumed. Given in alternate years; not offered 2015-16.

Bi 181. Introduction to Computational Biology and Bioinformatics. 9 units (3-0-6); *second term*. *Prerequisites:* Bi 8, CS 2, or instructor's permission. Biology is becoming an increasingly data-intensive science. Many of the data challenges in the biological sciences are distinct from other scientific disciplines because of the complexity involved. This course will introduce key computational, probabilistic, and statistical methods that are common in computational biology and bioinformatics. We will integrate these theoretical aspects to discuss solutions to common challenges that reoccur throughout bioinformatics including algorithms and heuristics for tackling DNA sequence alignments, phylogenetic reconstructions, evolutionary analysis, and population and human genetics. We will discuss these topics in conjunction with common applications including the analysis of high throughput DNA sequencing data sets and analysis of gene expression from RNA-Seq datasets. Instructor: Guttman.

Bi/BE 182. Animal Development and Genomic Regulatory Network Design. 9 units (3-0-6); *second term*. *Prerequisites:* Bi 8 and at least one of the following: Bi 111, Bi 114, or Bi 122 (or equivalents). This course is focused on the genomic control circuitry of the encoded programs that direct developmental processes. The initial module of the course is devoted to general principles of development, with emphasis on transcriptional regulatory control and general properties of gene regulatory networks (GRNs). The second module provides mechanistic analyses of spatial control functions in multiple embryonic systems, and the third treats the explanatory and predictive power of the GRNs that control body plan development in mammalian, sea urchin, and *Drosophila* systems. Grades or pass/fail. Instructors: Stathopoulos, Peter, Davidson. Given in alternate years; offered 2015-16.

Bi/CNS/NB 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. Given in alternate years; not offered 2015–16.

Bi/CNS/NB 185. Large Scale Brain Networks. 6 (2-0-4); third term.

This class will focus on understanding what is known about the large-scale organization of the brain, focusing on the mammalian brain. What large scale brain networks exist and what are their principles of function? How is information flexibly routed from one area to another? What is the function of thalamocortical loops? We will examine large scale networks revealed by anatomical tracing, functional connectivity studies, and mRNA expression analyses, and explore the brain circuits mediating complex behaviors such as attention, memory, sleep, multisensory integration, decision making, and object vision. While each of these topics could cover an entire course in itself, our focus will be on understanding the master plan--how the components of each of these systems are put together and function as a whole. A key question we will delve into, from both a biological and a theoretical perspective, is: how is information flexibly routed from one brain area to another? We will discuss the communication through coherence hypothesis, small world networks, and sparse coding. Instructor: Tsao. Given in alternate years, offered 2015–16.

CNS/Bi/EE/CS/NB 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/NB 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; not offered 2015–16.

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. Not offered 2015–16.

Bi 190. Systems Genetics. 6 units (2-0-4); third term. Prerequisites: Bi 122. Lectures covering how genetic and genomic analyses are used to understand biological systems. Emphasis is on genetic and genome-scale approaches used in model organisms such as yeast, flies, worms, and mice to elucidate the function of genes, genetic pathways and genetic networks. Instructor: Sternberg.

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

Bi 192. Introduction to Systems Biology. 6 units (2-0-4); first term. Prerequisites: Ma 1abc, and either Bi 8, CS1, or ACM 95 or instructor's permission. The course will explore what it means to analyze biology from a systems-level point of view. Given what biological systems must do and the constraints they face, what general properties must biological systems have? Students will explore design principles in biology, including plasticity, exploratory behavior, weak-linkage, constraints that deconstrain, robustness, optimality, and evolvability. The class will read the equivalent of 2-3 scientific papers every week. The format will be a seminar with active discussion from all students. Students from multiple backgrounds are welcome: non-biology or biology students interested in learning systems-level questions in biology. Limited enrollment. Not offered 2015-16.

Bi/CNS/NB 195. Mathematics in Biology. 9 units (3-0-6); first term. Prerequisites: Multi-variable calculus. This course develops the mathematical methods needed for a quantitative understanding of biological phenomena, including data analysis, formulation of simple models, and the framing of quantitative questions. Topics include: probability and stochastic processes, linear algebra and transforms, dynamical systems, scientific programming. Instructor: Meister. Given in alternate years; offered 2015-16.

Bi 199. Introduction to MATLAB for Biologists. 6 units (3-0-3); second term. This hands-on course provides an introduction to MATLAB's structure and syntax, writing of functions and scripts, image analysis, and data visualization. Instructor: Kennedy.

BE/Bi/NB 203. Introduction to Programming for the Biological Sciences Bootcamp. 6 units; summer. For course description, see Bioengineering.

Bi 204. Evolution of the Animal Body Plan. 6 units (2-0-4); third term. Prerequisite: Bi/BE 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. Given in alternate years; not offered 2015-16.

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/BE 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. Given in alternate years; not offered 2015-16.

Bi/CNS/NB 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; offered 2015-16.

Bi/CNS/NB 217. Central Mechanisms in Perception. 6 units (2-0-4); first term. Reading and discussions of behavioral and electrophysiological studies of the systems for the processing of sensory information in the brain. Given in alternate years; not offered 2015-16.

Bi/CNS/NB 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.

Bi/BE 227. Methods in Modern Microscopy. 12 units (2-6-4); second term. Prerequisites: Bi/BE 177 or a course in microscopy. Bi/BE 177 may be taken concurrently with this course. 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 as well as other techniques for optical sectioning such as light sheet fluorescence microscopy (also called single plane illumination microscopy, SPIM). During the class students will construct a light sheet microscope based on the openSPIM design. Alongside the building of a light sheet microscope, the course will consist of semi-independent modules organized around different imaging challenges using confocal microscopes. Early modules will include a lab using lenses to build a cloaking device. Most of the early modules will focus on three-dimensional reconstruction of fixed cells and tissues. Later modules will include time-lapse confocal analysis of living cells and embryos. Students will also utilize the microscopes in the Beckman Institute Biological Imaging Facility to learn more advanced techniques such as spectral unmixing and fluorescence correlation spectroscopy. 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: Collazo. Given in alternate years; offered 2015–16.

Bi/CNS/BE/NB 230. Optogenetic and CLARITY Methods in Experimental Neuroscience. 9 units (3–2–4); third term. Prerequisites: Graduate standing or Bi/CNS/NB 150 or equivalent (e.g. Bi/CNS/NB 164). The class covers the theoretical and practical aspects of using (1) optogenetic sensors and actuators to visualize and modulate the activity of neuronal ensembles; and (2) CLARITY approaches for anatomical mapping and phenotyping using tissue-hydrogel hybrids. Topics include: opsin design (including natural and artificial sources), delivery (genetic targeting, viral transduction), light activation requirements (power requirements, wavelength, fiberoptics, LEDs), compatible readout modalities (electrophysiology, imaging); design and use of methods for tissue clearing (tissue stabilization by polymers/hydrogels and selective extractions, such as of lipids for increased tissue transparency and macromolecule access). Class will discuss applications to neuronal circuits (case studies based on recent literature). The class offers hands-on lab exposure for opsin delivery, recording of light-modulated activity, and CLARITY tissue clearing, imaging, and 3D reconstruction of fluorescent samples. Instructor: Gradinaru.

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/ESE 246. Molecular Geobiology Seminar. 6 units (2–0–4). For course description, see Geological and Planetary Sciences.

CNS/Bi/NB 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 literature-based discussions covering research methods, scientific concepts and logic, research strategies and general principles of modern biology. Students will learn to critique papers in a wide range of fields, including molecular biology, developmental biology, genetics and neuroscience. Graded pass/fail. Instructor: Prober.

Bi 250 b. Topics in Systems Biology. 9 units (3-0-6); third 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. Instructors: Elowitz, Bois.

Bi/CNS/NB 250 c. 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/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 labs in the Division of Biology and Biological Engineering 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/NB 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 97. Undergraduate Research. *Units to be arranged; any term. Prerequisites: advanced BEM and instructor's permission.* This course offers advanced undergraduates the opportunity to pursue research on a business problem individually or in a small group. Graded pass/fail.

BEM 101. Selected Topics in Business Economics and Management. *Units to be determined by arrangement with the instructor; offered by announcement.* Topics to be determined by instructor. Instructors: Staff, visiting lecturers.

BEM 102. 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. Prerequisites: Ec 11 required; one of the following: Ec 122, Ge/ESE 118, Ma 1/103, MA 112a, MA 112b.* 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. Instructors: Roll.

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); first term. Prerequisites: One of the following: Ec 122, Ge/ESE 118, Ma 1/103, MA 112a, MA 112b, or instructor's permission; BEM 103 strongly recommended; some familiarity with differential equations is helpful. An introduction to option pricing theory and risk management in the discrete-time, binomial tree model, and the continuous-time Black-Scholes-Merton framework. Both the partial differential equations approach and the martingale approach (risk-neutral pricing by expected values) will be developed. The course will cover the basics of Stochastic, Ito Calculus. Instructors: Cvitanic.

BEM 106. Competitive Strategy. 9 units (3-0-6); second 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 2015-16.

BEM 107. Applied Corporate Finance and Investment Banking. 9 units (3-0-6); third term. Prerequisites: 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. Instructors: Cornell.

BEM 109. Fixed-Income and Credit-Risk Derivatives. 9 units (3-0-6); second term. Prerequisites: BEM 105. An introduction to the models of interest rates, credit/default risk, and risk management. The focus is on continuous time models used in the practice of Financial Engineering for pricing and hedging fixed income securities. Two main models for credit risk are considered: structural and reduced form/intensity models. Instructors: Cvitanic.

BEM 110. Venture Capital. 9 units (3-0-6); second term. Prerequisites: BEM 102, 103. An introduction to the theory and practice of venture capital financing of 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 and detailed examples. Topics include: The history of VC; VC stages of financing; financial returns to private equity; LBOs and MBOs; people versus ideas; biotech; IPOs; and CEO transitions. Instructors: Ewens.

BEM 111. Quantitative Risk Management. 9 units (3-0-6); third term. Prerequisites: GE/ACM 118, BEM 105, or Ma 112. 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 113. Financial Markets Laboratory. 9 units (3-3-3); second term. *Prerequisite:* BEM 103. Financial economics is rather abstract and mathematical, and its value is difficult to ascertain from merely observing real-world financial markets, which operate in a complex environment where many key variables either remain unobserved or cannot be measured reliably. In this class, students will learn about the theories of asset pricing, options, investments performance evaluation, corporate finance, and banking/insurance through participation in a series of online market games. Grading will be based on a mixture of trading performance, written and oral reports. Not offered 2015-16.

BEM 114. Behavioral Finance. 9 units (3-0-6); third term. *Prerequisites:* Students are recommended (but not required) to take BEM 103 to become familiar with some basic concepts in finance. Much of modern financial economics works with models in which agents are fully rational, in that they maximize expected utility and use Bayes' law to update their beliefs. Behavioral finance is a large and active field that develops and studies models in which some agents are less than fully rational. Such models have two building blocks: limits to arbitrage, which makes it difficult for rational traders to undo the dislocations caused by less rational traders; and psychology, which provides guidance for the kinds of deviations from full rationality we might expect to see. We discuss these two topics and consider a number of applications: asset pricing; individual trading behavior; the origin of bubbles; and financial crises. Instructor: Jin.

BEM/Ec 118. Environmental Economics. 9 units (3-0-6); first 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). Not offered 2015-16.

BEM/Ec 131. Market Design. 9 units (3-0-6); first term. *Prerequisites:* Ec 11 or equivalent. In this course we will study the design of markets and other market-like processes to address resource allocation and information extraction problems. We will cover the basic principles underlying the design process, as well as the practical considerations that arise when designing markets. Some examples include auctions (for spectrum, Treasury bills, IPO's, greenhouse gas permits, electricity), markets (cap and trade systems for pollution abatement or fishery management, scheduling, prediction), and matching systems (for college admissions, housing allocations, kidney exchange). Instructors: Ledyard.

BEM/Ec 150. Business Analytics. 9 units (3-0-6); third term. *Prerequisites:* GE/ESE 118 or Ec 122, and knowledge of R. This class teaches how to use

very large, cross-media datasets to infer what variables influence choices and trends of economic and business interest. Topics include database management, cleaning and visualization of data, statistical and machine learning methods, natural language processing, social and conventional media, personal sensors and devices, sentiment analysis, and controlled collection of data (including experiments). Grades are based on hands-on data analysis homework assignments and detailed analysis of one dataset. Instructor: Camerer.

BEM/Ec 185. Political Economy of Corporate Governance. *9 units (3-0-6). Prerequisites: 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 problems they face; the interaction between history, financial market structure, and the ownership of very large firms. Each student is expected to write two substantial papers—drafts will be read by instructor and revised by students. Not offered 2015–16.

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

Ch/ChE 9. Chemical Synthesis and Characterization for Chemical Engineering. *9 units (1-6-2).* For course description, see Chemistry.

ChE 10. Introduction to Chemical Engineering. *1 unit (1-0-0); second term.* 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 15. Introduction to Chemical Engineering Computation. *9; second term. (3-0-6). Prerequisites: Ma 2 and ChE 62.* Introduction to the solution of engineering problems through the use of the computer. Elementary programming in Matlab is taught, and applied to solving chemical engineering problems in data analysis, process simulation, and optimization. No previous knowledge of computer programming is assumed. Instructor: Flagan.

ChE 62. Separation Processes. *9 units (3-0-6); first term.* Equilibrium staged separations. Membrane separations. Absorption. Distillation. Liquid-liquid extraction. Introduction to mass transfer. Instructor: Seinfeld.

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. Instructors: Tirrell, Ismagilov.

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 outlining the proposed project, and clearly identifying its design component to the faculty mentor for the thesis and the chemical engineering option representative, 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 62 and ChE 63 ab, 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 ab 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: Kornfeld, Shapiro, Davis.

ChE 105. Dynamics and Control of Chemical Systems. *9 units (3-0-6); third term.* *Prerequisites:* ACM 95 ab or concurrent registration, or instructor's permission. Analysis of linear dynamic systems. Feedback control. Stability of closed-loop control systems. Root locus, Frequency response, and Nyquist analysis. Feedforward, cascade, and multivariable control systems. Instructor: Seinfeld.

ChE/BE/MedE 112. Design, Invention, and Fundamentals of Microfluidic Systems. *9 units (3-0-6); second term.* This course combines three parts. First, it will cover fundamental aspects of kinetics, mass-transport, and fluid physics that are relevant to microfluidic systems. Second, it will provide an understanding of how new technologies are invented and reduced to practice. Finally, students in the course will work together to design microfluidic systems that address challenges in Global Health, with an emphasis on students' inventive contributions and creativity. Students will be encouraged and helped, but not required, to develop their inventions further by working

with OTT and entrepreneurial resources on campus. Participants in this course benefit from enrollment of students with diverse backgrounds and interests. For chemical engineers, suggested but not required courses are ChE 101 (Chemical Reaction Engineering) and ChE 103abc (Transport Phenomena). Students are encouraged to contact the instructor to discuss enrollment. Instructor: Ismagilov.

ChE 114. Solid State NMR Spectroscopy For Materials Chemistry.

9 units (3-3-3); second Term. Prerequisites: Ch 21abc or instructor's permission. Principles and applications of solid state NMR spectroscopy will be addressed with focus on structure and dynamics characterization of organic and inorganic solids. Topics include basic principles of NMR phenomena in solid state, high resolution techniques such as magic angle spinning (MAS), cross-polarization (CP) MAS, Double Rotation (DOR) and multiple-quantum MAS (MQMAS) for half integer quadrupole nuclei, and multiple pulse experiments for dipolar decoupling and recoupling, which expect to cover NMR methods that are routinely employed in studies of organic and inorganic materials chemistry. Hands-on experience will be provided via laboratory course on solid NMR spectrometers. Not offered 2015–16.

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. Introduction into the gas-phase processing techniques used in the fabrication of electronic materials and devices. Kinetic theory of gases. Surface chemistry and gas-surface interaction dynamics. Film deposition techniques: physical and chemical vapor deposition, atomic layer epitaxy, liquid-phase epitaxy, molecular beam epitaxy. Introduction into plasmas and their role in patterned etching and layer deposition. Charging damage during plasma processing. Determination of key parameters that control the ion energy and flux to the wafer surface. Not offered 2015–16.

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: Vici.

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: Vici.

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. Instructors: Giapis, Vivic.

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: Giapis, Vivic.

ChE 130. Biomolecular Engineering Laboratory. 9 units (1–5–3); third term. Prerequisites: ChE 63 ab, ChE 101 (may be taken 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, Vivic.

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. Not offered 2015–16.

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. Not offered 2015-16.

ESE/ChE 158. Aerosol Physics and Chemistry. 9 units (3-0-6); second term; Open to graduate students and seniors with instructor's permission. For description, see Environmental Science and Engineering.

ChE/BE 163. Introduction to Biomolecular Engineering. 12 units (3-0-9); first term. Prerequisites: Bi/Ch 110 or instructor's permission and CS 1 or equivalent. 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 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. Not offered 2015-16.

ChE/BE/MedE 188. Molecular Imaging. 9 units (3-0-6); second term. Prerequisites: Bi/Ch 110, ChE 101 and ACM 95 or equivalent. This course will cover the basic principles of biological and medical imaging technologies including magnetic resonance, ultrasound, nuclear imaging, fluorescence, bioluminescence and photoacoustics, and the design of chemical and biological probes to obtain molecular information about living systems using these modalities. Topics will include nuclear spin behavior, sound wave propagation, radioactive decay, photon absorption and scattering, spatial encoding, image reconstruction, statistical analysis, and molecular contrast mechanisms. The design of molecular imaging agents for biomarker detection, cell tracking, and dynamic imaging of cellular signals will be analyzed in terms of detection limits, kinetics, and biological effects. Participants in the course will develop proposals for new molecular imaging agents for applications such as functional brain imaging, cancer diagnosis, and cell therapy. Instructor: Shapiro.

ChE 190. Special Problems in Chemical Engineering. Up to 9 units by arrangement; any term. Prerequisites: Instructor's permission and adviser's approval must be obtained before registering. Special courses of readings or laboratory instruction. The student should consult a member of the faculty and prepare a definite program of reading, computation, theory and/or experiment. The student must submit a summary of progress at midterm and, at the end of the quarter, a final assignment designed in consultation with the instructor. This course may be credited only once. Grading: either grades or pass/fail, as arranged with the instructor. Instructors: Staff.

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 (a), Reisman, Miller (b).

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. *Satisfies the menu requirement of the Caltech core curriculum.* Not offered 2015–16.

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 x. Experimental Methods in Solar Energy Conversion. 6 units (1–3–2); first, second, third terms. 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. Instructor: Mendez.

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 or Ch 3 x. Ch 4 a is a prerequisite for Ch 4 b. 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 focuses on the synthesis and analysis of organic molecules; Ch 4 b focuses on the synthesis and analysis of inorganic and organometallic molecules. Ch 4 a, second term; Ch 4 b, third term. Instructor: Mendez.

Ch 5 ab. Advanced Techniques of Synthesis and Analysis. Ch 5 a 12 units (1–9–2), second term; Ch 5 b 12 units (1–9–2), first term. *Prerequisites:* 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). Part b not offered 2015–16.

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, scanning probe microscopies, and UHV surface methods. The two terms can be taken in any order. Instructor: Weitekamp.

Ch 7. Advanced Experimental Methods in Bioorganic Chemistry. 9 units (1-6-2); second 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 powerful contemporary methods used in chemical biology, including polypeptide synthesis and the selective labeling and imaging of glycoproteins in cells. Experiments will address 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. Instructors: Hsieh-Wilson.

Ch 8. Experimental Procedures of Synthetic Chemistry. 9 units (1-6-2); first term. Prerequisites: Ch 1 ab and Ch 3 a or Ch 3 x. Previous or concurrent enrollment in Ch 41 is strongly recommended. Introduction to the synthesis of organic and organometallic compounds, and to methods of separation, purification, and spectroscopic characterization used in chemical research. Instructor: Mendez.

Ch/ChE 9. Chemical Synthesis and Characterization for Chemical Engineering. 9 units (1-6-2); third term. Prerequisites: Ch 1 ab and Ch 3 a or Ch 3 x. Previous or concurrent enrollment in Ch 41 is strongly recommended. Instruction in synthesis, separation, purification, and physical and spectroscopic characterization procedures of model organic and inorganic materials, with emphasis on chemical reactions such as polymerization, catalysis, and light absorption and emission. Enrollment priority given to chemical engineering majors. Instructor: Mendez.

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 or Ch 3 x, 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, Hoelz.

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. Also, introductory treatment of separations, chromatography and mass spectrometry. Instructors: TBD, Shahgholi.

Ch 15. Chemical Equilibrium and Analysis Laboratory. 10 units (0-6-4); first term. Prerequisites: Ch 1 ab, Ch 3 a or Ch 3 x, 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. Instructors: Dalleska.

Ch 21 abc. Physical Chemistry. 9 units (3-0-6); first, second, third terms. Prerequisites: Ch 1 ab, Ph 2 a or Ph 12 a, Ma 2; Ma 3 is recommended. Atomic and molecular quantum mechanics, spectroscopy, thermodynamics, statistical mechanics, and chemical kinetics. Instructors: Okumura, Cai, Beauchamp.

Ch 24. Introduction to Biophysical Chemistry: Spectroscopy. 9 units (3-0-6); second term. Prerequisites: Ch 1 ab, Ph 2 a or Ph 12 a, Ma 2 and Ch 21 a. 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: Ch 1 ab, Ph 2 a or Ph 12 a, Ma 2; 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. Prerequisites: Ch 1 ab or instructor's permission. The synthesis, structure, and mechanisms of reactions of organic compounds. Instructors: Dougherty (a), Hsieh-Wilson (b), Fu (c)

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 82/182. Senior Thesis Research. 9 units; first, second, third terms. Prerequisite: instructor's permission. Three terms of Ch 82/182 are to be completed

during the junior and/or senior year of study. Ch 182 is taken only by students pursuing a joint B.S./M.S. degree in Chemistry. At the end of the third term, students enrolled in Ch 82 will present a thesis of approximately 20 pages (excluding figures and references) to the mentor and the Chemistry Curriculum and Undergraduate Studies Committee. The thesis must be approved by both the research mentor and the CUSC. Students enrolled in Ch 182 will present a Masters Thesis, as described in requirements for the Masters degree. An oral thesis defense will be arranged by the CUSC in the third term for all enrollees. The first two terms of Ch 82/182 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. Strong oral presentation is an essential skill for successful job interviews and career advancement. Graded pass/fail. Instructors: Zewail, Bikle.

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

Ch 102. Introduction to Inorganic Chemistry. 9 units (3-0-6); third term. *Prerequisites: Ch 41 ab.* Structure and bonding of inorganic species with special emphasis on spectroscopy, ligand substitution processes, oxidation-reduction reactions, organometallic and biological inorganic chemistry. Instructors: 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 organo-transition metal compounds. Systematics of synthesis, bonding, and reactivities of commonly encountered classes of transition metal compounds. Instructor: Agapie.

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. Not offered 2015-16.

Ch 120 ab. Nature of the Chemical Bond. *Ch 120 a: 9 units (3-0-6), first term; Ch 120 b: (1-1-7), second term. 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) second term; Ch 121 b (1-1-7) first term. Prerequisites: 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. The homework for the 1st 5 weeks emphasizes computer-based solutions. For the exams and 2nd 5 weeks of the homework each student selects a short research project and uses atomistic simulations to solve it. For part b each student selects a more extensive 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. Prerequisites: Ch 21 abc or instructor's permission.* This course provides an introduction to small molecule X-ray crystallography. Topics include symmetry, space groups, diffraction by crystals, the direct and reciprocal lattice, Patterson and direct methods for phase determination, and structure refinement. It will cover both theoretical and applied concepts and include hands-on experience in data collection, structure solution and structure refinement. Instructor: Takase.

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

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. Instructors: Giapis, Vici.

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); *third term.* *Prerequisites: instructor's permission.* 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. Chemical Dynamics. 9 units (3-0-6); *second term.* *Prerequisites: Ch 21 abc and Ch 41 abc, or equivalent, or instructor's permission.* Introduction to the kinetics and dynamics of chemical reactions. Topics include scattering cross sections, rate constants, intermolecular potentials, classical two-body elastic scattering, reactive scattering, nonadiabatic processes, statistical theories of unimolecular reactions, photochemistry, laser and molecular beam methods, theory of electron transfer, solvent effects, condensed phase dynamics, surface reactions, isotope effects. Instructor: Okumura.

Ch/ChE 140 ab. Principles and Applications of Semiconductor Photoelectrochemistry. 9 units (3-0-6); *second, third terms.* *Prerequisite: APb/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 2015-16.

Ch 143. NMR Spectroscopy for Structural Identification. 9 units (3-0-6); *third term.* *Prerequisites: Ch 41 abc.* This course will address both one-dimensional and two-dimensional techniques in NMR spectroscopy which are essential to elucidating structures of organic and organometallic samples. Dynamic NMR phenomena, multinuclear, paramagnetic and NOE effects will also be covered. An extensive survey of multipulse NMR methods will also contribute to a clear understanding of two-dimensional experiments. (Examples for Varian NMR instrumentation will be included.) Instructor: Virgil.

Ch 144 ab. Advanced Organic Chemistry. 9 units (3-0-6); *second term.* *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. Instructor: Dougherty (a). Part b not offered 2015–16.

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. Not offered 2015–16.

Ch 146. Bioorganic Chemistry of Nucleic Acids. 9 units (3–0–6). *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 2015–16.

Ch/ChE 147. Polymer Chemistry. 9 units (3–0–6), second term. *Prerequisite:* Ch 41 abc. An introduction to the chemistry of polymers, including synthetic methods, mechanisms and kinetics of macromolecule formation, and characterization techniques. Instructor: Grubbs. Course will be offered second term. Instructor: Grubbs.

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

Ch 149. Tutorial in Organic Chemistry. 6 units (2–0–4); first term. *Prerequisites:* Ch 41 abc and instructor's permission. Discussion of key principles in organic chemistry, with an emphasis on reaction mechanisms and problem-solving. This course is intended primarily for first-year graduate students with a strong foundation in organic chemistry. Meets during the month of October. Graded pass/fail. Instructors: Fu, Reisman.

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). Part b not offered 2015–16.

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. Instructor: Peters (a). Part b not offered 2015–16.

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. Biochemistry and Biophysics of Macromolecules and Molecular Assemblies. 9 units (3–0–6); *first.* 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.

BMB/Bi/Ch 173. Biophysical/Structural Methods. 9 units (3–0–6); *second.* For course description, see Biochemistry and Molecular Biophysics.

BMB/Bi/Ch 174. Molecular Machines in the Cell. 9 units (3–0–6); *third.* For course description, see Biochemistry and Molecular Biophysics.

ESE/Ch 175. Physical Inorganic Chemistry of Natural Waters. 9 units (3–0–6); *second term.* For course description, see Environmental Science and Engineering.

ESE/Ch 176. Physical Organic Chemistry of Natural Waters. 9 units (3–0–6); *third term.* For course description, see Environmental Science and Engineering.

BMB/Ch 178. Macromolecular Function: Kinetics, Energetics, and Mechanisms. 9 units (3–0–6); *first term.* 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; first, second, third terms. 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. Instructors: Gray, Winkler.

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. Prerequisites: Ch 125 abc or Ph 125 abc or concurrent registration or equivalent; Ch 143. A detailed presentation of some of the important concepts in magnetic resonance unified by the spin density operator formalism. Topics will include both classic phenomena and recent developments, especially in solid-state and two-dimensional NMR. Not offered 2015–16.

Ch 227 ab. Advanced Topics in Chemical Physics. 9 units (3–0–6); third term. Prerequisites: Ch 125 abc or Ph 125 abc or equivalent. The goal of this course is to utilize approaches derived from the chemico-physical to understand what are often considered complex biological problems. The course is a literature driven course with a strong emphasis on student participation. Part b not offered 2015–16. Instructors: Heath (a).

Ch 228. Dynamics and Complexity in Physical and Life Sciences. 9 units (3–0–6); third term. This course is concerned with the structure-dynamics-function of complex systems, from materials to chemical and biological functions. We will address principles of elementary dynamics as they relate to the nature of the structures involved. An overview of modern techniques, such as those involving lasers, NMR, diffraction and imaging will be overviewed. Applications include areas in physics, chemistry and biology, covering phenomena of interest, from coherence and chaos to molecular recognition and self-assembly. Course requirement, which includes writing a “science paper” and presentation, will be outlined in the first meeting. Instructors: Zewail.

BMB/Ch 230. Macromolecular Structure Determination with Modern X-ray Crystallography Methods. 12 units (2–4–6); Third term. For course description, see Biochemistry and Molecular Biophysics.

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: Campbell, Parker.

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

Ch 247. Organic Reaction Mechanisms. 9 units (3-0-6); second term. *Prerequisites:* Ch 41 abc, Ch 242 a recommended. This course will discuss and uncover useful strategies and tactics for approaching complex reaction mechanisms prevalent in organic reactions. Topics include: cycloaddition chemistry, rearrangements, radical reactions, metal-catalyzed processes, photochemical reactions among others. Recommended only for students interested in advanced study in organic chemistry or related fields. Not offered 2015-16.

Ch 250. Advanced Topics in Chemistry. 3 units; third term. Content will vary from year to year; topics are chosen according to the interests of students and staff. Visiting faculty may present portions of this course. In Spring 2016 the class will be a seminar course in pharmaceutical chemistry with lectures by industrial researchers from both discovery (medicinal chemistry) and development (process chemistry) departments. Instructors: Fu, Grubbs, Stoltz.

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 2015-16.

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 ab. Computational Mechanics. 9 units (3-0-6); *first, second terms. Prerequisite: Ae/AM/ME/CE 102 abc or Ae/GE/ME 160 ab, or instructor's permission.* Numerical methods and techniques for solving initial boundary value problems in continuum mechanics (from heat conduction to statics and dynamics of solids and structures). Finite difference methods, direct methods, variational methods, finite elements in small strains and at finite deformation for applications in structural mechanics and solid mechanics. Solution of the partial differential equations of heat transfer, solid and structural mechanics, and fluid mechanics. Transient and nonlinear problems. Computational aspects and development and use of finite element code. Not offered 2015-16.

CE/ME 112 ab. Hydraulic Engineering. 9 units (3-0-6); *second, third terms. Prerequisites: ME 11 abc, ME 12 abc; ACM 95/100 or equivalent (may be taken concurrently).* A survey of topics in hydraulic engineering: open channel and pipe flow, subcritical/critical flow and the hydraulic jump, hydraulic structures (weirs, inlet and outlet works, dams), hydraulic machinery, hydrology, river and flood modeling, solute transport, sediment mechanics, groundwater flow. Instructor: Hall.

AM/CE/ME 150 abc. Graduate Engineering Seminar. 1 unit; *each term.* For course description, see Applied Mechanics.

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 2015-16.

ME/CE 163. Mechanics and Rheology of Fluid-Infiltrated Porous Media. 9 units (3-0-6). For course description, see Mechanical Engineering.

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

CE/ME/Ge 173. Mechanics of Soils. 9 units (3-0-6); second term. Prerequisites: *Continuum Mechanics - Ae/Ge/ME 160a*. Basic principles of stiffness, deformation, effective stress and strength of soils, including sands, clays and silts. Elements of soil behavior such as stress-strain-strength behavior of clays, effects of sample disturbance, anisotropy, and strain rate; strength and compression of granular soils; consolidation theory and settlement analysis; and critical state soil mechanics. Instructors: Asimaki.

ME/CE/Ge 174. Mechanics of Rocks. 9 units (3-0-6); third term. For course description, see Mechanical Engineering.

CE 180. Experimental Methods in Earthquake Engineering.

9 units (1-5-3); first 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. Not offered 2015–16.

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. A faculty mentor will oversee a student proposed, independent research or study project to meet the needs of graduate students. Graded pass/fail. The consent of a faculty mentor and a written report is required for each term.

CE 201. Advanced Topics in Civil Engineering. 9 units (3-0-6). The faculty will prepare courses on advanced topics to meet the needs of graduate students.

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.

CE/Ge/ME 222. Earthquake Source Processes, Debris Flows, and Soil Liquefaction: Physics-based Modeling of Failure in Granular Media. 6 units (2-0-4); third term. A seminar-style course focusing on granular

dynamics and instabilities as they relate to geophysical hazards such as fault mechanics, debris flows, and liquefaction. The course will consist of student-led presentations of active research at Caltech and discussions of recent literature. Not offered 2015–2016.

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: Perona.

CNS/SS/Psy/Bi 102 ab. Brains, Minds, and Society. *9 units*

(3-0-6); second, third terms. Prerequisites: Bi/CNS/NB 150 and CNS/Bi/Ph/CS/NB 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: Camerer, O'Doherty. Offered 2015–16.

Psy/CNS 105 ab. Frontiers in Neuroeconomics. *5 units (1.5-0-3.5).* For course description, see Psychology.

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; part a offered spring term; bc not offered 2015–16.

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 2015–16.

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

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

Bi/CNS/NB 153. Brain Circuits. 9 (3–0–6); *Second Term*. *Prerequisites: Bi/CNS/NB 150 or equivalent*. For course description, see Biology.

CMS/CS/CNS/EE 155. Machine Learning Data Mining. 12 units (3–3–6); *second term*. For course description, see Computing and Mathematical Sciences.

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

Bi/CNS/NB 157. Comparative Nervous Systems. 9 units (2–3–4); *third term*. For course description, see Biology.

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

CS/CNS/EE 159. Advanced Topics in Machine Learning. 9 units (3–0–6); *third term*. For course description, see Computer Science.

Bi/CNS/NB 162. Cellular and Systems Neuroscience Laboratory. 12 units (2–7–3); *third term*. *Prerequisites: Bi/CNS/NB 150 or instructor's permission*. For course description, see Biology.

Bi/CNS/NB 164. Tools of Neurobiology. 9 units (3–0–6); *second term*. *Prerequisites: Bi/CNS/NB 150 or equivalent*. 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/NB 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. Not Offered 2015–16.

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

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

Bi/CNS/NB 185. Large Scale Brain Networks. *6 (2-0-4); third term.* For course description, see Biology.

CNS/Bi/EE/CS/NB 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. Given in alternate years; offered 2015-16.

CNS/Bi/Ph/CS/NB 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.

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

Bi/CNS/NB 195. Mathematics in Biology. *9 (3-0-6).* For course description, see Biology.

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

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

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

Bi/CNS/BE/NB 230. Optogenetic and CLARITY Methods in Experimental Neuroscience. 9 units (3–2–4); third term. For course description, see Biology.

CNS/Bi/NB 247. Cerebral Cortex. 6 units (2–0–4); second term. *Prerequisite:* Bi/CNS/NB 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. Not offered 2015–16.

Bi/CNS 250 c. 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.

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

CNS/Bi/NB 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. Given in alternate years; offered 2015–16.

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

SS/Psy/CNS 285. Topics in Social, Cognitive, and Decision Sciences. 3 units (3–0–0); first, second, third terms. For course description, see Social Sciences.

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.

COMPUTER SCIENCE

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 (2–6–1); second term.

Prerequisites: CS 1 or equivalent. CS 2 is a demanding course in programming languages and computer science. Topics covered include data structures, including lists, trees, and graphs; implementation and performance analysis of common algorithms; algorithm design principles, in particular recursion and dynamic programming; concurrency and network programming; basic numerical computation methods. Heavy emphasis is placed on the use of compiled languages and development tools, including source control and debugging. The course includes weekly laboratory exercises and written homework covering the lecture material and program design. The course is intended to establish a foundation for further work in many topics in the computer science option. Instructors: Barr, Desbrun.

CS 3. Introduction to Software Engineering. 9 units (2–4–3); third term.

Prerequisites: CS 2 or equivalent. CS 3 is a practical introduction to software engineering with an emphasis on understanding and minimizing risk in large software projects. Students will work in teams on a course-long project. Topics covered include revision control, code reviews, testing and testability, code readability, API design, refactoring, and documentation. The course provides opportunities to present your work to the class, and emphasizes working with other people's code, both that of classmates and pre-existing frameworks. Not offered 2015–16.

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: Desbrun.

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: Pinkston, Vanier.

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: Familiarity with C equivalent to having taken the CS 11 C track.* 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: Schulman.

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

EE/CS 52 ab. Microprocessor Systems Laboratory. 9 units (3-6-0) second term; 6 units (1-5-0) third term; second, third terms. 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: Blanquart, Murray.

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 Projects in Computer Science. *Units are assigned in accordance with work accomplished. Prerequisites: Consent of supervisor is required before registering.* Supervised research or development in computer science by undergraduates. The topic must be approved by the project supervisor, and a formal final report must be presented on completion of research. This course can (with approval) be used to satisfy the project requirement for the CS major. Graded pass/fail. Instructor: Staff.

CS 90. Undergraduate Reading in Computer Science. *Units are assigned in accordance with work accomplished. Prerequisites: Consent of supervisor is required before registering.* Supervised reading in computer science by undergraduates. The topic must be approved by the reading supervisor, and a formal final report must be presented on completion of the term. 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 115. Functional Programming. *9 units (3-4-2); third term. Prerequisites: CS 1 and CS 4.* This course is both a theoretical and practical introduction to functional programming, a paradigm which allows programmers to work at an extremely high level of abstraction while simultaneously avoiding large classes of bugs that plague more conventional imperative and object-oriented languages. The course will introduce and use the lazy functional language Haskell exclusively. Topics include: recursion, first-class functions, higher-order functions, algebraic data types, polymorphic types, function composition, point-free style, proving functions correct, lazy evaluation, pattern matching, lexical scoping, type classes, and modules. Some advanced topics such as monad transformers, parser combinators, dynamic typing, and existential types are also covered. Instructor: Vanier.

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: Staff.

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. Not offered 2015–16.

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. Not offered 2015–16.

CS 121. Introduction to Relational Databases. 9 units (3–0–6); first term.

Prerequisites: 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. Instructor: Pinkston.

CS 122. Database System Implementation. 9 units (3–3–3); second term.

Prerequisites: CS2, CS38, CS 121 and familiarity with Java, or instructor's permission. This course explores the theory, algorithms, and approaches behind modern relational database systems. Topics include file storage formats, query planning and optimization, query evaluation, indexes, transaction processing, concurrency control, and recovery. Assignments consist of a series of programming projects extending a working relational database, giving hands-on experience with the topics covered in class. The course also has a strong focus on proper software engineering practices, including version control, testing, and documentation. Not offered 2015–16.

CS 123. Projects in Database Systems. 9 units (0–0–9); third term. *Prerequisites:* CS121 and CS122.

Students are expected to execute a substantial project in databases, write up a report describing their work, and make a presentation. Not offered 2015–16.

CS 124. Operating Systems. (3–0–6); Second term. *Prerequisites:* CS 24.

This course explores the major themes and components of modern operating systems, such as kernel architectures, the process abstraction and process scheduling, system calls, concurrency within the OS, virtual memory management, and file systems. Students must work in groups to complete a series of challenging programming projects, implementing major components of an instructional operating system. Most programming is in C, although some IA32 assembly language programming is also necessary. Familiarity with the material in CS 24 is strongly advised before attempting this course. Instructor: Pinkston.

EE/Ma/CS 126 ab. Information Theory. 9 units (3–0–6); first, second terms.

Prerequisites: Ma 2. 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 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 2015-16.

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

EE/CS/EST 135. Power System Analysis. 9 units (3-3-3); second term. For course description, see Electrical Engineering.

CS 138. Computer Algorithms. 9 units (3-0-6); third term. 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. Instructor: Schulman.

CMS/CS 139. Analysis and Design of Algorithms. 12 units (3-0-9); second term. For course description, see Computation and Mathematical Sciences.

CS 142. Distributed Computing. (3-0-6); third term. Prerequisites: CS 24, CS 38. Programming distributed systems. Mechanics for cooperation among concurrent agents. Programming sensor networks and cloud computing applications. Applications of machine learning and statistics by using parallel computers to aggregate and analyze data streams from sensors. Not offered 2015-16.

CS/EE 143. Communication Networks. 9 units (3-3-3); first term. Prerequisites: Ma 2, Ma 3, CS 24 and CS 38, or instructor permission. 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. Instructor: Low.

CMS/CS/EE 144. Networks: Structure Economics. 12 units (3-3-6); second term. For course description, see Computing and Mathematical Sciences.

CS/EE 145. Projects in Networking. 9 units (0-0-9); third term. Prerequisites: Either CMS/CS/EE 144 or CS 141 b in the preceding term, or instructor permission. Students are expected to execute a substantial project in networking, write up a report describing their work, and make a presentation. Instructor: Wierman.

CS/EE 146. Advanced Networking. 9 units (3-3-3); third term. Prerequisites: 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. Not offered 2015-16.

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

SS/CS 149. Introduction to Algorithmic Economics. 9 units (3-0-6). Prerequisites: Ma 3, CS 24 and CS 38, or instructor permission. For course description, see Social Science.

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. Not offered 2015-16.

CS 151. Complexity Theory. 12 units (3-0-9); 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. Not offered 2015-16.

CS/SS 152. Introduction to Data Privacy. 9 units (3-0-6); first term. Prerequisites: Ma 3, CS 24 and CS 38, or instructor's permission. How should we define privacy? What are the tradeoffs between useful computation on large datasets and the privacy of those from whom the data is derived? This course will take a mathematically rigorous approach to addressing these and other questions at the frontier of research in data privacy. We will draw connections with a wide variety of topics, including economics, statistics, information theory, game theory, probability, learning theory, geometry, and approximation algorithms. Not offered 2015-16.

CS 153. Current Topics in Theoretical Computer Science. 9 units (3-0-6); second 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.
Instructor: Umans.

CMS/CS/CNS/EE 155. Machine Learning Data Mining. 12 units (3-3-6); second term. For course description see Computing and Mathematical Sciences.

CS/CNS/EE 156 ab. Learning Systems. 9 units (3-0-6); first, third 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 2015-16.

CS/CNS/EE 159. Advanced Topics in Machine Learning. 9 units (3-0-6); third term. *Prerequisites:* CS 155; strong background in statistics, probability theory, algorithms, and linear algebra; background in optimization is a plus as well. This course focuses on current topics in machine learning research. This is a paper reading course, and students are expected to understand material directly from research articles. Students are also expected to present in class, and to do a final project. Instructors: Yue.

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. Not offered 2015–16.

CS 179. GPU Programming. 9 units (3-3-3); third term. Prerequisites: Working knowledge of C. Some experience with computer graphics algorithms preferred, but not required. The use of Graphics Processing Units for computer graphics rendering is well known, but their power for general parallel computation is only recently being explored. Parallel algorithms running on GPUs can often achieve up to 100x speedup over similar CPU algorithms. This course covers programming techniques for the Graphics processing unit, focusing on visualization and simulation of various systems. Labs will cover specific applications in graphics, mechanics, and signal processing. The course will introduce the OpenGL Shader Language (GLSL) and nVidia's parallel computing architecture, CUDA. Labwork will require extensive programming. Instructor: Barr, 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 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. Not offered 2015–16.

CNS/Bi/EE/CS/NB 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/NB 187. Neural Computation. 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.

BE/CS 196 ab. Design and Construction of Programmable Molecular Systems. 12 units (3-6-3) second term; (2-8-2) third term. For course description, see Bioengineering.

ACM/CS/EE 218. Statistical Inference. 9 units (3-0-6); third term. For course description, see Applied and Computational Mathematics.

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

SS/CS 241. Topics in Algorithmic Economics. 9 units (3-0-6). For course description, see Social Science.

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 2015-16.

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.*

COMPUTING AND MATHEMATICAL SCIENCES

CMS/ACM 104. Linear Algebra and Applied Operator Theory. 12 units (3-0-9); first term. *Prerequisites: Undergraduate prerequisites: Ma 1 abc (analytic track), Ma 2, and ACM 95 ab; or instructor's permission.* This course introduces the theory and applications of linear algebra and linear analysis. Lectures and homework will require the ability to understand and produce mathematical proofs. Theoretical topics may include topology of metric spaces, structure of Banach and Hilbert spaces, examples of normed spaces, duality, structure of linear operators, spectral theory, functional calculus for linear operators, and calculus in Banach spaces. Applications will be drawn from signal processing, numerical analysis, optimization, approximation, differential equations, control, and other areas. Emphasis will be placed on geometry and convexity. Instructors: Tropp.

CMS/ACM 113. Mathematical Optimization. 9 units (3-0-6); first term. *Prerequisites: ACM 95/100 ab, ACM 11, or instructor's permission.* Corequi-

site: It is suggested that students take CMS/ACM 104 concurrently. This class studies mathematical optimization from the viewpoint of convexity. Topics covered include duality and representation of convex sets; linear and semidefinite programming; connections to discrete, network, and robust optimization; relaxation methods for intractable problems; as well as applications to problems arising in graphs and networks, information theory, control, signal processing, and other engineering disciplines. Instructors: Chandrasekaran.

CMS/ACM 116. Introduction to Stochastic Processes and Modeling. 9 units (3-0-6); first term. Prerequisites: Ma 2, Ma 3 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. Instructors: Owhadi.

CMS/CS 139. Analysis and Design of Algorithms. 12 units (3-0-9); second term. Prerequisites: Ma 2, Ma 3, Ma/CS 6a, CS 21, CS 38/138, CMS/ACM/EE 116, or instructor's permission.

This course covers advanced topics in the design and analysis of algorithms. Topics are drawn from approximation algorithms, randomized algorithms, online algorithms, streaming algorithms, and other areas of current research interest in algorithms. Instructors: Vidick.

CMS/CS/EE 144. Networks: Structure Economics. 12 units (3-3-6); second term. Prerequisites: Ma 2, Ma 3, Ma/CS 6a, and CS 38, or instructor's permission.

Social networks, the web, and the internet are essential parts of our lives and we all depend on them every day, but do you really know what makes them work? This course studies the "big" ideas behind our networked lives. Things like, what do networks actually look like (and why do they all look the same)? How do search engines work? Why do memes spread the way they do? How does web advertising work? For all these questions and more, the course will provide a mixture of both mathematical analysis and hands-on labs. The course assumes students are comfortable with graph theory, probability, and basic programming. Instructors: Wierman.

CMS/CS/CNS/EE 155. Machine Learning Data Mining. 12 units (3-3-6); second term. Prerequisites: background in algorithms and statistics (CS/CNS/EE/NB 154 or CS/CNS/EE 156 a or instructor's permission).

This course will cover popular methods in machine learning and data mining, with an emphasis on developing a working understanding of how to apply these methods in practice. This course will also cover core foundational concepts underpinning and motivating modern machine learning and data mining approaches. This course will be research-oriented, and will cover recent research developments. Instructors: Yue.

ACM/CS/EE/CMS 218. Statistical Inference. 12 units (3-0-9); second term. See course description in Applied and Computational Mathematics.

CMS 290 abc. Computing and Mathematical Sciences Colloquium. 1 unit; first, second, third terms. Registration open to graduate students only. This course is a research seminar covering topics at the intersection of mathematics, computation, and their applications. Speakers are internationally recognized researchers from mathematics, applied mathematics, statistics, computer science, electrical engineering, control theory, and related disciplines. Attendance is required. Staff.

CMS 300. Research in Computing and Mathematical Sciences. Hours and units by arrangement. Research in the field of computing and mathematical science. By arrangement with members of the staff, properly qualified graduate students are directed in research. Instructors: Staff.

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, CDS 112 or CDS 140 (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, 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: Murray.

CDS 110. Introduction to Feedback Control Systems. 12 units (3-0-9); first term. Prerequisites: Ma 1abc and Ma 2/102 or equivalents. An introduction to analysis and design of feedback control systems, including classical control theory in the time and frequency domain. Input/output modeling of dynamical systems using differential equations and transfer functions. Stability and performance of interconnected systems, including use of block diagrams, Bode plots, the Nyquist criterion, and Lyapunov functions. Design of feedback controllers in state space and frequency domain based on stability, performance and robustness specifications. Instructors: Murray.

CDS 112. Control System Design. 9 units (3-0-6); second term. Prerequisites: CDS 110. Optimization-based design of control systems, including optimal control and receding horizon control. Robustness and uncertainty management in feedback systems through stochastic and deterministic methods. Introductory random processes, Kalman filtering, and norms of signals and systems. Instructor: Doyle.

CDS 140. Introduction to Dynamics. 9 units (3-0-6); second term. Prerequisites: Ma 2/102 or equivalent, CMS/ACM 104. Basics topics in dynamics for continuous state systems in continuous and discrete time, using linear and nonlinear differential equations and maps. Topics include equilibria/invariant sets, stability, Lyapunov functions/invariants, attractors and periodic solutions. Introduction to structural stability, bifurcations and eigenvalue crossing conditions. Instructor: Murray.

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

CDS 212. Introduction to Modern Control. 9 units (3-0-6); second term. Prerequisites: Ma2/102, CMS/ACM 104, CDS 110. 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); third term. Prerequisites: CDS 212. 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. Not offered 2015-16.

CDS 240. Nonlinear Dynamical Systems. 9 units (3-0-6); third term. Prerequisites: CDS 140. Analysis of nonlinear dynamical systems modeled using differential equations, including invariant and center manifolds, bifurcations, limit cycles, regular and singular perturbations, the method of averaging, input/output stability. Additional advanced topics may be included based on student and instructor interests. Instructors: Doyle, Murray.

Ae/CDS/ME 251 ab. Closed Loop Flow Control. 9 units; (3-0-6 a, 1-3-5- b). For course description, see Aerospace.

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 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, second 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.

Ec 97. Undergraduate Research. Units to be arranged; any term. *Prerequisites:* Advanced economics and instructor's permission. This course offers advanced undergraduates the opportunity to pursue research in Economics individually or in a small group. Graded pass/fail.

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

Ec 101. Selected Topics in Economics. Units to be determined by arrangement with the instructor; offered by announcement. Topics to be determined by instructor. Instructors: Staff, visiting lecturers.

Ec 105. Industrial Organization. 9 units (3–0–6); first term. *Prerequisites:* 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—especially those related to internet commerce—in detail. Each student is expected to write one substantial paper. Not offered 2015–16.

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. Not offered 2015–16.

Ec/Psy 109. Frontiers in Behavioral Economics. 9 units (3–0–6), first term. *Prerequisites:* Ec 11. Behavioral economics studies agents who are biologically limited in computational ability, willpower and pure self-interest. An important focus is how those limits interact with economic institutions and firm behavior. This reading-driven course will cover new papers that are interesting and draw attention to a topic of importance to economics. Readings will cover lab and field experiments, axiomatic models of behavioral phenomena, and welfare. Each weekly discussion will begin with a 10-minute overview, then an inspection of the paper's scientific machinery,

judge whether its conclusions are justified, and speculate about the scope of its generalizability. It should help students as referees and as writers. Assignments are two 1000-word summary-critiques. Instructor: Camerer.

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 2015-16.

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

BEM/Ec 131. Market Design. 9 units (3-0-6); *first term.* 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. Instructor: Saito, Border.

Ec 122. Econometrics. 9 units (3-0-6); *first term.* *Prerequisites:* Ma 3. The application of statistical techniques to the analysis of economic data. Instructors: 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 2015-16.

Ec/SS 124. Identification Problems in the Social Sciences. 9 units (3-0-6); *second term.* *Prerequisites:* Ec 122. Statistical inference in the social sciences is a difficult enterprise whereby we combine data and assumptions to draw conclusions about the world we live in. We then make decisions, for better or for worse, based on these conclusions. A simultaneously intoxicating and sobering thought! Strong assumptions about the data generating process can lead to strong but often less than credible (perhaps incredible?) conclusions about our world. Weaker assumptions can lead to weaker but more credible conclusions. This course explores the range of inferences that are possible when we entertain a range of assumptions about how data is generated. We explore these ideas in the context of a number of applications of interest to social scientists. Instructors: Sherman.

Ec/SS 129. Economic History of the United States. 9 units (3-0-6); *second term.* *Prerequisites:* Ec 11. An examination of certain analytical and quantitative tools and their application to American economic development. Each

student is expected to write two substantial papers - drafts will be read by instructor and revised by students. Not offered 2015–16.

Ec/SS 130. Economic History of Europe from the Middle Ages to the Twentieth Century. 9 units (3–0–6); third term. Prerequisites: Ec 11.

Employs the theoretical and quantitative techniques of economics to help explore and explain the development of the European cultural area between 1000 and 1980. Topics include the rise of commerce, the demographic transition, the Industrial Revolution, and changes in inequality, international trade, social spending, property rights, and capital markets. Each student is expected to write nine weekly essays and a term paper. Instructors: Hoffman.

Ec 135. Economics of Uncertainty and Information. 9 units (3–0–6); first term. Prerequisites: Ec 11, Ma 2b. An analysis of the effects of uncertainty and information on economic decisions. Included among the topics are individual and group decision making under uncertainty, expected utility maximization, insurance, financial markets and speculation, product quality and advertisement, and the value of information. Instructor: Agranov.

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. Not offered 2015–16

Ec 145. Public Finance. 9 units (3–0–6), first term. Prerequisite: Ec 11 or equivalent. An intermediate-level course on the economics of the public sector. Material is chosen from welfare economics, public expenditure theory and practice, taxation theory and practice, federalism, and public choice theory. Instructor: Ledyard.

BEM/Ec 150. Business Analytics. 9 units (3–0–6); third term. Prerequisites: ACM 118 or Ec 122, and knowledge of R. 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.

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.

Ec 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 economics. Graded pass/fail. Instructor: Staff.

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.

EE/ME 7. Introduction to Mechatronics. 6 units (2-3-1); second term. Mechatronics is the multi-disciplinary design of electro-mechanical systems. This course is intended to give the student a basic introduction to such systems. The course will focus on the implementations of sensor and actuator systems, the mechanical devices involved and the electrical circuits needed to interface with them. The class will consist of lectures and short labs where the student will be able to investigate the concepts discussed in lecture. Topics covered include motors, piezoelectric devices, light sensors, ultrasonic transducers, and navigational sensors such as accelerometers and gyroscopes. 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 Devices. 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. Overview of electronic properties of semiconductor that are significant to device operation for integrated circuits. Silicon device fabrication technology. Metal-semiconductor contacts, p-n junctions, bipolar transistors, photoconductors, diodes, transistors, CCDs, MOS/MOSFET/CMOS imagers, temperature sensors, magnetic sensors, thermoelectricity, piezoresistivity, piezoelectrics, etc. Instructors: Choo.

EE 44. Circuits and Systems. 12 units (4-0-8); *first term. Prerequisites: Ph1 abc, should be taken concurrently with Ma 2 and Ph 2 a.* Fundamentals of circuits and network theory, circuit elements, linear circuits, terminals and port presentation, nodal and mesh analysis, time-domain analysis of circuits and systems, sinusoidal response, introductory frequency domain analysis, transfer functions, poles and zeros, time and transfer constants, network theorems, transformers. Instructors: Hajimiri.

EE 45. Electronics Laboratory. 12 units (3-3-6); *second term. Prerequisites: EE 44.* Fundamentals of electronic circuits and systems. Lectures on diodes, transistors, small-signal analysis, frequency-domain analysis, application of Laplace transform, gain stages, differential signaling, operational amplifiers, introduction to radio and analog communication systems. Laboratory sessions on transient response, steady-state sinusoidal response and phasors, diodes, transistors, amplifiers. 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 ab. Microprocessor Systems Laboratory. 9 units (3-6-0) *second term*; 6 units (1-5-0) *third term*; *second, third terms.* Prerequisites: 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. Instructors: George.

EE/CS 53. Microprocessor Project Laboratory. 12 units (0-12-0); *first, second, third terms. Prerequisites: EE/CS 52 ab 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. May be repeated for credit. 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); third term. *Prerequisites:* EE 40 and EE 45. A structured laboratory course that gives the student the opportunity to design and build a simple analog electronics project. 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: Hajimiri.

EST/EE/ME 109. Energy Technology and Policy. 9 units (3-0-6); first term. For course description, see Energy Science and Technology.

EE 111. Signal-Processing Systems and Transforms. 9 units (3-0-6); first term. *Prerequisites:* Ma 1. An introduction to continuous and discrete time

signals and systems with emphasis on digital signal processing systems. Study of the Fourier transform, Fourier series, z-transforms, and the fast Fourier transform as applied in electrical engineering. Sampling theorems for continuous to discrete-time conversion. Difference equations for digital signal processing systems, digital system realizations with block diagrams, analysis of transient and steady state responses, and connections to other areas in science and engineering. Instructors: Vaidyanathan.

EE 112. Introduction to Digital Signal Processing. 9 units (3-0-6); second term. Prerequisites: EE 111 or equivalent. Math 3 recommended. Fundamentals of digital signal processing, digital filtering, recursive and non recursive filters, linear phase and minimum phase systems, digital filter structures, allpass filters and applications, quantization and stability analysis, round-off noise calculations, Nyquist and sub-Nyquist sampling, elements of multi-rate signal processing, reconstruction of sparsely sampled signals, statistical signal processing and sensor array signal processing, and applications in various areas. Offered 2015–16. Instructor: Vaidyanathan.

EE 113. Feedback and Control Circuits. 9 units (3-3-3); third term. Prerequisites: 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 design, build, analyze, test, and measure the circuits and systems discussed in the lectures. Instructors: George.

EE/MedE 114 ab. Analog Circuit Design. 12 units (4-0-8); second, third terms. Prerequisites: EE 44 or equivalent. Analysis and design of analog circuits at the transistor level. Emphasis on design-oriented analysis, quantitative performance measures, and practical circuit limitations. Circuit performance evaluated by hand calculations and computer simulations. Recommended for juniors, seniors, and graduate students. Topics include: review of physics of bipolar and MOS transistors, low-frequency behavior of single-stage and multistage amplifiers, current sources, active loads, differential amplifiers, operational amplifiers, high-frequency circuit analysis using time- and transfer constants, high-frequency response of amplifiers, feedback in electronic circuits, stability of feedback amplifiers, and noise in electronic circuits, and supply and temperature independent biasing. A number of the following topics will be covered each year: trans-linear circuits, switched capacitor circuits, data conversion circuits (A/D and D/A), continuous-time Gm.C filters, phase locked loops, oscillators, and modulators. Instructors: Hajimiri. Offered 2015–16.

EE/MedE 115. Micro-/Nano-scales Electro-Optics. 9 units (3-0-6); first term. Prerequisites: Introductory electromagnetic class and consent of the instructor. The course will cover various electro-optical phenomena and devices in the micro-/nano-scales. We will discuss basic properties of light, imaging,

aberrations, eyes, detectors, lasers, micro-optical components and systems, scalar diffraction theory, interference/interferometers, holography, dielectric/plasmonic waveguides, and various Raman techniques. Topics may vary. Not offered 2015–16.

Ph/APh/EE/BE 118 ab. Physics of Measurement. 9 units (3–0–6); *first and second terms.* For course description, see Physics.

Ph/APh/EE/BE 118 c. Physics of Measurement. 9 units (3–0–6); *third terms.* For course description, see Physics.

EE 119 abc. Advanced Digital Systems Design. 9 units (3–3–3) *first, second term; 9 units (1–8–0) third term; first, second, third terms.* *Prerequisite: EE/CS 52 ab or CS/EE 181 a or CS 24.* 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 2015–16.

EE 120. Topics in Information Theory. 9 units (3–0–6); *third term.*

This class introduces information measures such as entropy, information divergence, mutual information, information density from a probabilistic point of view, and discusses the relations of those quantities to problems in data compression and transmission, statistical inference, language modeling, game theory and control. Topics include information projection, data processing inequalities, sufficient statistics, hypothesis testing, single-shot approach in information theory, large deviations. Prerequisites: undergraduate calculus and probability; desirable but not required: EE126a. Instructors: Kostina.

EE/MedE 124. Mixed-mode Integrated Circuits. 9 units (3–0–6); *first term.* *Prerequisites: EE 45 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. Instructors: 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. Offered 2015–16. Instructor: Pedroni.

EE/Ma/CS 126 ab. Information Theory. 9 units (3–0–6); *first, second terms. Prerequisites:* 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 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); *second term. Prerequisites:* Ma 2. This course develops 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, 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, turbo 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: Kostina.

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 2015–16.

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); *first term.* For course description, see Applied Physics.

EE/APh 131. Light Interaction with Atomic Systems - Lasers. 9 units (3-0-6); second term. Prerequisites: APh/EE 130. Light-matter interaction, spontaneous and induced transitions in atoms and semiconductors. Absorption, amplification, and dispersion of light in atomic media. Principles of laser oscillation, generic types of lasers including semiconductor lasers, mode-locked lasers. Frequency combs in lasers. The spectral properties and coherence of laser light. Instructor: Yariv.

APh/EE 132. Special Topics in Photonics and Optoelectronics. 9 units (3-0-6); third term. For course description, see Applied Physics.

EE/CS/EST 135. Power System Analysis. 9 units (3-3-3); second term. Prerequisites: EE 44, Ma 2, or equivalent. Phasor representation, 3-phase transmission system, per-phase analysis; power system modeling, transmission line, transformer, generator; network matrix, power flow solution, optimal power flow; Swing equation, stability, protection; demand response, power markets. Instructors: Low.

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

CMS/CS/EE 144. Networks: Structure Economics. 12 units (3-3-6); second term. For course description, see Computing and Mathematical Sciences.

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.

EE/CNS/CS 148. Selected Topics in Computational Vision. 9 units (3-0-6); third term. 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. Instructors: 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); third term. Prerequisite: EE 45. Foundations of circuit theory—electric fields, magnetic fields, transmission lines, and Maxwell's equations, with engineering applications. Instructor: Yang.

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.

CMS/CS/CNS/EE 155. Machine Learning Data Mining. 12 units (3-3-6); second term. For course description, see Computing and Mathematical Sciences.

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.

Ge/EE/ESE 157 c. Remote Sensing for Environmental and Geological Applications. 9 units (3-3-3). For course description, see Geological and Planetary Sciences.

CS/CNS/EE 159. Advanced Topics in Machine Learning. 9 units (3-0-6); third term. For course description, see Computer Science.

EE 160. Random Variables and Stochastic Processes. 9 units (3-0-6); first term. Prerequisites: Math 2, Math 3. Introduction to fundamental ideas and techniques of stochastic analysis. Random variables, expectation and conditional expectation, joint distributions, covariance, moment generating functions, central limit theorem, weak and strong laws of large numbers, discrete time stochastic processes, stationarity, power spectral densities, Gaussian processes, Poisson processes. The course develops applications in areas such as communication, signal processing, networks and queues. 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. Given in alternate years. Not offered 2015–16.

EE 163 ab. Communication Theory. 9 units (3–0–6); second, third terms.

Prerequisites: EE 111; ACM/EE 116 or equivalent. Mathematical models of communication processes; signals and noise as random processes; sampling; modulation; spectral occupancy; intersymbol interference; synchronization; optimum demodulation and detection; signal-to-noise ratio and error probability in digital baseband and carrier communication systems; linear and adaptive equalization; maximum likelihood sequence estimation; multipath channels; parameter estimation; hypothesis testing; optical communication systems. Part a offered 2015–16; Part b not offered 2015–16. Instructor: Staff.

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. Given in alternate years; offered 2015–16. Instructor: Hassibi.

EE/BE/MedE 166. Optical Methods for Biomedical Imaging and Diagnosis. 9 units (3–1–5); third 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. Given in alternate years; not offered 2015–16.

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. Karhunen-Loeve and discrete cosine transforms. The bit allocation problem. Subband coding. Practical algorithms for image and video compression. Not offered 2015–16.

ACM/EE 170. Mathematics of Signal Processing. 12 units (3-0-9); third term. See course description in Applied and Computational Mathematics.

EE/Aph 180. Nanotechnology. 6 units (3-0-3); first term. This course will explore the techniques and applications of nanofabrication and miniaturization of devices to the smallest scale. It will be focused on the understanding of the technology of miniaturization, its history and present trends towards building devices and structures on the nanometer scale. Examples of applications of nanotechnology in the electronics, communications, data storage and sensing world will be described, and the underlying physics as well as limitations of the present technology will be discussed. 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.

EE/BE/MedE 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. Not offered 2015-16.

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

EE/MedE 187. VLSI and ULSI Technology. 9 units (3-0-6); third 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 2015-16.

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

ACM/CS/EE/CMS 218. Statistical Inference. 3-0-6; third term. For course description, see Applied and Computational Mathematics.

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 2015–16.

EE 243. Special Topics in Laser Physics and Quantum Electronics. 6 units (3-0-3); third term. The course will cover advanced topics in laser physics and quantum electronics including: Quantum Noise, Coherence, New Resonator concepts, and applications to ultra high speed optical communication, sensing and metrology. The final examination will be in the form of an individualized study assignment. Instructor: Yariv.

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 2. Energy and Society. 9 units (3-2-4); third term. Prerequisites: Ph 1ab, Ma 1ab, Ch 1ab. A discussion of where our energy comes from and how we use it. Resources of oil, coal, natural gas, oil sands, and shale gas. Alternative energy sources: hydroelectric, nuclear, wind, geothermal, solar photovoltaic, and solar thermal. Combustion, steam engines, gas turbines, internal-combustion engines, fuel cells and batteries. The electricity grid and transmission lines, agriculture and biofuels, freight and passenger transportation, and heating and lighting of buildings. Not offered on a pass/fail basis. Satisfies the menu requirement of the Caltech core curriculum. Instructor: Rutledge.

EST/EE/ME 109. Energy Technology and Policy. 9 units (3-0-6); first term. Prerequisites: Ph 1abc, Ch 1ab and Ma 1abc. A discussion of how energy technology interacts with government policy. Renewable sources and the electricity grid. The shale gas revolution and fracking impacts. Electric vehicles and car mileage standards. Coal mining by mountaintop removal and pollution. Peak oil and the debate on limits to growth. Resource models and climate-change policy. Instructors: Rutledge.

EE/CS/EST 135. Power System Analysis. 9 units (3-3-3); second term. For course description, see Electrical Engineering.

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: Ravichandran.

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, fourth 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. *Enrollment is limited to students in E&AS options (and PMA options in fourth term) and priority is given to seniors.* Instructors: Pierce, Readhead, Smith.

E/H/Art 89. New Media Arts in the 20th and 21st Centuries. *9 units (3-0-6); second term. Prerequisites: none.* This course will examine artists' work with new technology, fabrication methods and media from the late 19th Century to the present. Major artists, exhibitions, and writings of the period will be surveyed. While considering this historical and critical context, students will create their own original new media artworks using technologies and/or fabrication methods they choose. Possible approaches to projects may involve robotics, electronics, computer programming, computer graphics, mechanics and other technologies. Students will be responsible for designing and fabricating their own projects. Topics may include systems in art, the influence of industrialism, digital art, robotics, telematics, media in performance, interactive installation art, and technology in public space. Artists studied may include Eadweard Muybridge, Marcel Duchamp, Vladimir Tatlin, John Cage, Jean Tinguely, Stelarc, Survival Research Laboratories, Lynne Hershman Leeson, Eduardo Kac, Natalie Jeremenjenko, Heath Bunting, Janet Cardiff and others. Instructors: Mushkin.

E 102. Entrepreneurial Development. *9 units (3-0-6); first 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. Only E 102 b will be offered 2015–16. 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. Not offered 2015–16.

E/ME/MedE 105 ab. Design for Freedom from Disability. *9 units (3-0-6); second, third terms.* This Product Design class focuses on people with Disabilities and is done in collaboration with Rancho Los Amigos National Rehabilitation Center. Students visit the Center to define products based upon actual stated and observed needs. Designs and testing are done in collaboration with Rancho associates. Speakers include people with assistive needs, therapists and researchers. Classes teach normative design methodologies as adapted for this special area. Instructors: Pickar.

E 110. Principles of University Teaching and Learning in STEM. *2 units (1-0-1); first term.* Research on university-level teaching and learning in Science, Technology, Engineering, and Mathematics (STEM) disciplines has progressed rapidly in recent years; a well-established body of evidence-based principles now exists to inform instructors and students at the undergraduate and graduate levels. Increasingly, future PIs and faculty are called upon to demonstrate knowledge of and ability to apply established teaching and assessment practices, as well as to analyze the efficacy of new approaches. In this course, weekly interactive meetings will provide focused overviews and guided application of key pedagogical research, such as prior knowledge and misconceptions, novice-expert differences, and cognitive development as applied to university teaching. We will also explore emerging university teaching and learning practices and their theoretical basis (e.g., the flipped classroom, online learning). Readings will inform in-class work and students will apply principles to a project of their choice. Instructors: Horii.

E 120. Data Visualization Projects. *6 units (2-0-4); third term.* This course will provide students with a forum for discussing and working through challenges of visualizing students' data using techniques and principles from graphic design, user experience design, and visual practices in science and engineering. Working together, we will help create and edit students'

graphics and other visual forms of data to improve understanding. We will consider the strengths and weaknesses of communicating information visually in drawing, design and diagramming forms such as flow charts, brainstorming maps, graphs, illustrations, movies, animation, as well as public presentation materials, depending on the needs of students' projects. Our approach will be derived from design principles outlined by Edward Tufte and others. The course is targeted towards students across disciplines using visual display and exploration in research. There is no pre-requisite, but students should be competent in acquiring and processing data. Instructors: Mushkin and Lombeyda.

ENGLISH

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/Wr 84. Writing About Science. 9 units (3-0-6); *third term*. Instruction and practice in writing about science and technology for non-specialist audiences. The course considers how to convey complex technical information in clear, engaging prose in a variety of contexts. Readings in different genres (newspaper journalism, creative non-fiction, and advocacy) raise issues for discussion and serve as models for preliminary writing assignments. A more substantial final project will be on a topic and in the genre of the student's choosing. Includes oral presentation. *Satisfies the Institute scientific writing requirement and the option oral communications requirement for humanities majors.* Instructor: Hall, S.

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, 88, and 89 to the additional HSS requirements, and all other courses in this series will receive Institute credit. Instructor: Hall, J.

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 89. Writing The News - Journalistic Writing. *9 units (3-0-6); third term.* This class explores journalistic writing — writing that pays close attention to fact, accuracy, clarity and precision. It examines various aspects of the craft, such as reporting and interviewing, theme and scene, character and storytelling. It looks closely at how traditional print journalism offers up the news through newspapers - their structure, rules, process and presentation. It looks at new media, its process and principles. It also explores long-form journalistic writing. Students will produce numerous stories and other writing during the class, including profiles, issues, and reviews. Several of these will be offered for publication in The California Tech. There may be visits by professional journalists and off-campus excursions, including an outing to the Los Angeles Times. Instructor: Kipling.

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. En 98 is intended primarily for English majors and minors. Interested students should confer with an English faculty member and agree upon a topic before registering for the course. 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 103. Introduction to Medieval British Literature. *9 units (3-0-6); first term.* This course offers a tour of major (as well as some minor) genres and works written in Britain prior to 1500. Far from a literary “dark age,” the Middle Ages fostered dramatic experiments in narrative form, bequeathing to modern literature some of its best-loved genres and texts. We will practice reading in Middle English—the language of Chaucer and his contemporaries—while we concentrate on the following questions: how did these texts circulate among readers? How do they establish their authority? What kinds of historical and cultural currents to they engage? Texts may include the lives of saints, the confessions of sinners, drama, lyrics, romances, selections from Chaucer’s *Canterbury Tales*, and Malory’s *Morte Darthur*. Readings will be in Middle and modern English. Instructors: Jahner.

En 104. Imagining the Medieval in the Nineteenth Century. *9 units (3-0-6); third term.* Following the Enlightenment and amidst the Industrial Revolution, the late-eighteenth and nineteenth centuries saw a surging interest in the literature, lives, art, and architecture of the Middle Ages. In this course, we will explore how authors represented, invoked, and often idealized the medieval past—with its knights, peasants, saints, and monsters—as a way to think through the challenges—social, literary, political, aesthetic—of their own time. We will read several novels, poems, and treatises, including Henry David Thoreau’s essay, “Walking;” Mark Twain’s *A Connecticut Yankee in King Arthur’s Court*; Alfred Lord Tennyson’s *Idylls of the King*;

and others. Requirements for the course will include weekly response papers and two essays. Instructors: Saltzman.

En 105. Old English Literature. *9 units (3-0-6); first term.* “Moððe word fræt.” Want to learn how to read the riddle that begins with these words? This course will introduce students to Old English: the earliest form of the English language, spoken in England from roughly the years 450 to 1100. In studying the language, we will turn to its diverse and exciting body of literature, including one poem commemorating the brutal defeat by a Viking army and another based on the biblical story of Judith, who tricks the evil king Holofernes into sleeping with her—but not before slicing off his drunken head. We will also read a variety of shorter texts: laws, medical recipes, humorously obscene riddles. Successful completion of the course will give students a richer sense not only of the earliest period of English literature, but also of the English language as it is written and spoken today. No prior experience with Old or Middle English is necessary for this course. Instructors: Saltzman.

En 106. Literature and Law in Medieval England. *9 units (3-0-6); first term.* This course examines one of the most exciting and transformative periods in legal and literary history, the later Middle Ages. In England, this era witnessed the rise of lawyers, the advent of trial by jury, and the amassment of the common law. It saw kings fall, peasants revolt, and religious dissenters condemned for heresy. But it also saw the development of a sophisticated legal system and, alongside it, a burgeoning literary tradition. This class examines that literary tradition while also tracing some key legal developments of the period. We will read poetic texts together with relevant legal materials, including law codes, trial transcripts, and statutes. As we gain a basic introduction to medieval legal topics, we will also consider how poets represent and appropriate law, analyzing, for instance, how the figure of the witness informs genres like romance and hagiography. Certain readings will be in Middle English, but no previous experience with the language is required. Not offered 2015–16.

En 107. Medieval Romance. *9 units (3-0-6); third term.* The medieval term *romanz* designated both a language, French, and a genre, romance, dedicated to the adventures of knights and ladies and the villains, monsters, magic, and miles that stood in their way. This course explores key examples from the twelfth through the fifteenth centuries, while also examining evolutions in the form. We will consider how romances figured love and desire as well as negotiated questions of law, territory, and cultural difference. Authors and texts may include Chretien de Troyes, Marie de France, Gawain and the Green Knight, Arthurian legends, outlaw tales, and hagiography. Not offered 2015–16.

En 110. Saints, Sinners, and Sexuality in the Medieval World. *9 units (3-0-6); second 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 2015–16.

En 113 ab. Shakespeare's Career. *9 units (3-0-6); second, third terms.* 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. Not offered 2015–16.

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 2015–16.

En 118. Classical Mythology. *9 units (3-0-6); third term.* Why did the Greeks and Romans remain fascinated with the same stories of gods and demigods for more than a thousand years? On the other hand, how did they adapt those stories to fit new times and places? Starting with the earliest Greek poems and advancing through classical Athens, Hellenistic Alexandria, and Augustan Rome, we consider the history of writing poetry as a history of reading the past; the course also serves as an excellent introduction to ancient literary history at large. Readings may include Homer's 'Odyssey,' Hesiod, Aeschylus, Euripides, Apollonius Rhodius, Ovid, and Seneca. Instructor: Haugen.

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 2015–16.

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); first 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 2015–16.

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. Not offered 2015–16.

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 2015–16.

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); first 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. Not offered 2015–16.

En 127. Jane Austen. *9 units (3-0-6); third term.* This course will focus on the major novels of Jane Austen: *Northanger Abbey*, *Sense and Sensibility*, *Pride and Prejudice*, *Mansfield Park*, *Emma*, and *Persuasion*. Film and television adaptations will also be considered, and students may have the opportunity to read Austen's unfinished works, as well as related eighteenth- and nineteenth-century British fiction and non-fiction. Not offered 2015–16.

En 128. Modern and Contemporary Irish Literature. *9 units (3-0-6); third term.* 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. Instructor: Gilmartin.

En 129. Enlightenment Fiction. 9 units (3-0-6); second 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 2015–16.

En 131. Poe's Afterlife. 9 units (3-0-6); second term. 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 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 2015–16.

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 2015–16.

En 134. The Career of Herman Melville. 9 units (3-0-6), second 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 2015–16.

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 2015–16.

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 2015–16.

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 2015–16.

En 141. James and Wharton. 9 units (3–0–6); first 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 2015–16.

En 145. American Ethnic Literature. 9 units (3–0–6); second term. From the idea of the melting pot to contemporary debates about multiculturalism, the costs and benefits of assimilation have been crucial to understanding what it means to be American in the twentieth and twenty-first centuries. We will be reading novels, autobiographies, sociology, and other texts that describe the struggles of newcomers to adapt to an alien culture while also, often, trying to negotiate a meaningful relation to their native culture. Authors covered may include Anzia Yezierska, Maxine Hong Kingston, Frank Chin, Richard Rodriguez, Philip Roth, and T. C. Boyle. Not offered 2015–16.

En/F 160 ab. Introduction to Classical Hollywood Film. 9 units (3–0–6); first, second 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. Not offered 2015–16.

En/F 161. The New Hollywood. 9 units (3–0–6); second term. This course examines the post-classical era of Hollywood filmmaking with a focus

on the late 1960s through the 1970s, a period of significant formal and thematic experimentation. We will study American culture and politics as well as film in this era, as we consider the relation between broader social transformations and the development of new narrative conventions and cinematic techniques. We will pay particular attention to the changing film industry and its influence on this body of work. Films covered may include *Bonnie and Clyde*, *The Wild Bunch*, *The Last Picture Show*, *Jaws*, and *Taxi Driver*. Instructor: Jurca.

En 177. History of the English Language. *9 units (3–0–6); first term.* This course introduces students to the historical development of the English language, from its Proto-Indo-European roots through its earliest recorded forms (Old English, Middle English, and Early Modern English) up to its current status as a world language. English is a language that is constantly evolving, and students will gain the linguistic skills necessary for analyzing the features of its evolution. We will study the variation and development in the language over time and across regions, including variations in morphology, phonology, syntax, grammar, and vocabulary. We will also examine sociological, political, and literary phenomena that accompany and shape changes in the language. Not offered 2015–16.

En 178. Medieval Subjectivities. *9 units (3–0–6); second term.* In the seventeenth century, Descartes penned his famous expression “I think therefore I am!” and thus the modern subject was born—or so the simplified story goes. But long before the age of Descartes, the Middle Ages produced an astonishing range of theories and ideas about human selfhood, subjectivity, and interiority. For instance, writing from prison more than one thousand years earlier, Boethius came to realize that what distinguishes a human being from all other creatures is his capacity to “know himself.” The meaning of this opaque statement and others like it will command our attention throughout this course, as we explore the diverse, distinctive, and often highly sophisticated notions of subjectivity that developed in the literatures of the Middle Ages. We will take up questions of human agency, free will, identity, self-consciousness, confession, and secrecy as we encounter them in some of the most exciting texts written during the period, including (among others) Augustine’s *Confessions*, Prudentius’s *Psychomachia*, the Old English poem *The Wanderer*, the mystical writings of Margery Kempe and Julian of Norwich, and Chaucer’s *Troilus and Criseyde*. Not offered 2015–16.

En 179. Constituting Citizenship before the Fourteenth Amendment. *9 units (3–0–6); second term.* What can a slave’s narrative teach us about citizenship? How did the new nation identify citizens when its Constitution seemed so silent on the matter? And how did one tailor’s pamphlet result in one of the most massive restrictions of free speech in U.S. history? Our goal over the semester will be to sketch a story of African American literary production from the latter half of the eighteenth century to the Civil War and to tease out, through this literature, developing understandings of citizenship in the United States. We will read letters, poems, sermons, songs, constitutions and bylaws, short stories, and texts that simply defy easy categorization. We will also spend several sessions becoming familiar with

key newspapers and magazines—Freedom’s Journal, Frederick Douglass’s Paper, The Anglo-African Magazine, Christian Recorder, and The Crisis—to deepen our understanding of the kinds of things people were reading and writing on a regular basis and the kinds of arguments they were making. Writers up for discussion may include: Frederick Douglass, James Madison, Harriet Jacobs, Henry David Thoreau, Sojourner Truth, and David Walker. Not offered 2015–16.

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

En 181. 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 2015–16.

En 182. Literature and the First Amendment. 9 units (3–0–6); third 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: 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 185. 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 2015–16.

En 186. The Novel of Education. *9 units (3-0-6); third term.* What does it mean to be educated? This class will consider this question via a series of novels that take us from secondary school to the university, and from the nineteenth century to the present. Concentrating on British literature, with its compelling tendency to focalize historical anxieties about class, race and social reform through depictions of formal schooling practices, we too will consider these issues as we enter classrooms and eavesdrop on faculty conversations. At the same time, there will be ample scope to engage with more abstract questions about power, pedagogy, and alienation, and we will use our reading’s rich stock of schoolyard bullies, boarding school mean girls, struggling scholars and power-mad professors as the concrete anchor for such considerations. Authors read may include Dickens, Bronte, Waugh, Amis, Spark, Lodge, Ishiguro and Zadie Smith. Instructor: Gilmore.

En 190. Chaucer. *9 units (3-0-6); second term.* This course devotes itself to the writings of the diplomat, courtier, bureaucrat, and poet, Geoffrey Chaucer. Best known for the *Canterbury Tales*, Chaucer also authored dream visions, lyrics, and philosophical meditations. This course will introduce you to some better-known and lesser-known works in the Chaucerian corpus, while also exploring questions central to the production and circulation of literature in the fourteenth and fifteenth centuries. What did it mean to “invent” a literary work in late medieval England? How did Chaucer imagine himself as a writer and reader? What are the hallmarks of Chaucerian style, and how did Chaucer become the canonical author he is today? We will read Chaucer’s works in their original language, Middle English, working slowly enough to give participants time to familiarize themselves with syntax and spelling. No previous experience with the language is necessary. Instructor: Jahner.

En 191. Masterworks of Contemporary Latin American Fiction. *9 units (3-0-6); third term.* This course studies Latin America’s most influential authors in the 20th and 21st centuries, with a focus on short stories and novellas produced by the region’s avant-garde and “boom” generations. Authors may include Allende, Bombal, Borges, García Márquez, Quiroga, Poniatowska, and Vargas Llosa. All readings and discussions are in English. Not offered 2015–16.

En/H 193. Cervantes, Truth or Dare: Don Quixote in an Age of Empire. *9 units (3-0-6); second term.* Studies Cervantes’s literary masterpiece, *Don Quixote*, with a view to the great upheavals that shaped the early modern world: Renaissance Europe’s discovery of America; feudalism’s demise and the rise of mass poverty; Reformation and Counter-Reformation; extermination of heretics and war against infidels; and the decline of the Hapsburg dynasty. The hapless protagonist of *Don Quixote* calls into question the boundaries between sanity and madness, truth and falsehood,

history and fiction, objectivity and individual experience. What might be modern, perhaps even revolutionary, in Cervantes's dramatization of the moral and material dilemmas of his time? Conducted in English. Instructor: Wey-Gomez.

En/H 197. American Literature and the Technologies of Reading. *9 units (3-0-6); second term.* This course explores the material forms of American literature from the colonial era through the nineteenth century. We will study how and by whom books and other kinds of texts were produced, and how these forms shaped and were shaped by readers' engagement with them. Possible topics include the history of such printing technologies as presses, types, paper, ink, binding, and illustration; the business of bookmaking and the development of the publishing industry; the rise of literary authorship; the career of Benjamin Franklin; print, politics, and the American Revolution; and manuscript culture. Instructor: Hunter

ENGLISH AS A SECOND LANGUAGE

Please see page 290 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); first, second terms.* Communication and pronunciation in spoken English. Development of pronunciation, vocabulary, listening comprehension, and accuracy and fluency in speaking. Aspects of American culture will be discussed. The first 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. Instructor: Geasland.

ESL 107. Introductory Writing and Oral Presentation. *Noncredit; offered by announcement; third term.* The exploration of ideas in both oral and written English is crucial in a variety of academic settings. Whether writing a thesis or term paper, undertaking an oral exam, or presenting at a conference or seminar, the organization of ideas is central, of course, but the details of formatting, grammar, logic, word choice and delivery are a close second. This course includes frequent in-class oral presentations by students based on their current research interests, followed by detailed critiques of pronunciation and style and ample opportunity for practice to develop both English confidence and delivery skills. The writing portion of the course includes classroom exercises and editing practice will be based on student writing samples. Here, also, the emphasis will be on content, logic, formatting and grammar, work choices, as well as punctuation. The goals of the course include improvement of confidence and presentation skills, and the ability to communicate clearly and concisely in both oral and written English. Enrollment is limited, with priority given to graduate students. Instructor: Geasland.

ENVIRONMENTAL SCIENCE AND ENGINEERING

ESE 1. Introduction to Environmental Science and Engineering. 9 units (3-0-6); third term. Prerequisites: *Pb 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. Instructor: Leadbetter.

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 Problems in Environmental Science and Engineering. Up to 12 units by arrangement; any term. Prerequisites: instructor's permission. Special courses of readings or laboratory instruction. Graded pass/fail. Instructor: Staff.

ESE 101. Earth's Atmosphere. 9 units (3-0-6); first term. Composition of the atmosphere. Radiative transfer and the greenhouse effect. Scattering and absorption by gases, clouds, and aerosols. Feedbacks due to water vapor, clouds, ice, and vegetation. Transports of energy and momentum and their effects on the surface climate. Chemical reactions in the atmosphere affecting atmospheric ozone and air quality. Instructor: Ingersoll.

ESE 102. Earth's Oceans. 9 units (3-0-6); first term. Fundamentals of ocean dynamics: Ekman layers, wind-driven gyres, boundary currents, and overturning circulations. Oceanographic observational methods and phenomenology of the distribution of temperature, salinity, and tracers. Ocean biology and chemistry: simple plankton population models, Redfield ratios, air-sea gas exchange, productivity and respiration, weathering inputs, and carbon cycle basics. Fundamentals of past climate changes. Geochemical methods of inferring past ocean behavior, and changes of ocean circulations over Earth's history. Instructor: Adkins.

ESE 103. Earth's Biogeochemical Cycles. 9 units (3-0-6); second term. Global cycles of carbon, nitrogen and sulfur. Photosynthesis, respiration and net primary production. Soil formation, erosion, and carbon storage. Ecosystem processes, metrics, and function. Nutrient supply and limitation. Microbial processes underlying weathering, decomposition, and carbon remineralization. Stable isotope tracers in the carbon and hydrologic cycles. The human footprint on the Earth. Instructor: Wennberg.

ESE 104. Current Problems in Environmental Science and Engineering. 1 unit; first term. Discussion of current research by ESE graduate students, faculty, and staff. Instructor: Staff.

Bi/Ge/ESE 105. Evolution. 12 units (3–4–5); second term. For course description, see Biology.

ESE 106. Research in Environmental Science and Engineering. Units by arrangement; any term. Prerequisites: instructor's permission. Exploratory research for first-year graduate students and qualified undergraduates. Graded pass/fail. Instructors: Staff.

ESE 110 abc. Seminar in Environmental Science and Engineering. 1 unit; first, second, third terms. Seminar on current developments and research in environmental science and engineering. Graded pass/fail. Instructor: Adkins.

Ge/ESE 118. Methods in Data Analysis. 9 units (3–0–6); first term. Prerequisites: Ma 1 or equivalent. For course description, see Geology.

ESE 130. Atmosphere Dynamics. 9 units (3–0–6); first term. Prerequisites: ESE 101 or instructor's permission. Introduction to the physical balances and dynamical mechanisms governing Introduction to the dynamics of large-scale flows in the atmosphere. Governing equations and approximations that describe these rotation and stratification dominated flows. Topics include: conservation laws, equations of state, geostrophic and thermal wind balance, vorticity and potential vorticity dynamics, shallow water dynamics, atmospheric waves. Instructor: Bordoni.

ESE 131. Physical Oceanography. 9 units (3–0–6); second term. Prerequisite: ESE 102 or instructor's permission. Introduction to the physical balances and dynamical mechanisms governing ocean circulations. Topics include: Overview of observation systems; wind-driven planetary gyres and western boundary currents; buoyancy-driven circulations and abyssal flow; energetics of ocean circulations and combined effects of wind and buoyancy driving; meridional overturning circulations; thermocline models; mesoscale eddies; equatorial waves and response to wind driving at the equator; El Niño and the Southern Oscillation. Instructor: Thompson.

ESE 132. Tropical Atmosphere Dynamics. 9 units (3–0–6); third term. Prerequisite: ESE 130 or instructor's permission. Phenomenological description of tropical atmospheric circulations at different scales, and theories or models that capture the underlying fundamental dynamics, starting from the large-scale energy balance and moving down to cumulus convection and hurricanes. Topics to be addressed include: large-scale circulations such as the Hadley, Walker, and monsoonal circulations, the intertropical convergence zone, equatorial waves, convectively coupled waves, and hurricanes. Given in alternate years; not offered 2015–16.

ESE 133. Large-scale Atmosphere Dynamics. 9 units (3–0–6); second term. Prerequisite: ESE 130 or instructor's permission. Introduction to the global-

scale fluid dynamics of the atmosphere, beginning with an analysis of classical models of instabilities in atmospheric flows and leading to currently unsolved problems. Topics include barotropic Rossby waves and barotropic instability; the quasigeostrophic two-layer model and baroclinic instability; conservation laws for wave quantities and wave-mean flow interaction theory; turbulent fluxes of heat and momentum; geostrophic turbulence; genesis of zonal jets; Hadley cell dynamics. The course focuses on Earth's atmosphere but treats the circulation of Earth's atmosphere as part of a continuum of possible planetary circulations. Not offered 2015–16.

ESE 134. Cloud and Boundary Layer Dynamics. 9 units (3-0-6); *third term. Prerequisite: ESE 130 or instructor's permission.* Introduction to the dynamics of clouds and atmospheric boundary layers, from a phenomenological overview of cloud and boundary layer morphologies to closure theories for turbulence and convection. Topics include similarity theories for neutral and thermally stratified boundary layers; dry convective boundary layers; mixed-layer models; stably stratified boundary layers; moist thermodynamics and stability; stratocumulus and trade-cumulus boundary layers; shallow cumulus convection and deep convection. Given in alternate years; not offered 2015–16.

ESE 135. Topics in Atmosphere and Ocean Dynamics. 6 (2-0-4); *third term. Prerequisites: ESE 101/102 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, marine physical-biogeochemical interactions, and dynamics of El Niño and the Southern Oscillation. Instructors: Bordoni, Thompson.

ESE 137. Polar Oceanography. 9 units (3-0-6); *third term. Prerequisites: ESE 131 or instructor's permission.* This course focuses on the high latitude circulation of the Earth's ocean as well as the ocean's interaction with the cryosphere, including glaciers, ice shelves and sea ice. Topics covered include: water mass formation and modification processes, the dynamics of the Southern Ocean's overturning circulation, Arctic circulation, controls on sea distribution, the stability of marine-terminating ice sheets. Given in alternate years, not offered 2015–16.

ESE 138. Ocean Turbulence and Wave Dynamics. 9 units (3-0-6); *third term. Prerequisite: ESE 131 or instructor's permission.* Introduction to the dynamics of ocean mixing and transport with a focus on how these processes feed back on large-scale ocean circulation and climate. Topics include: vorticity and potential vorticity dynamics, planetary and topographic Rossby waves, inertia-gravity waves, mesoscale eddies, turbulent transport of tracers, eddy diffusivity in turbulent flows, frontogenesis and submesoscale dynamics, diapycnal mixing. This course will also include a discussion of observational techniques for measuring mesoscale and small-scale processes in the ocean. Given in alternate years; not offered 2015–16.

Ge/ESE 139. Introduction to Atmospheric Radiation. 9 units (3-0-6); *third term.* For course description in Geological and Planetary Sciences.

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

Ge/ESE 146. Stable isotope biogeochemistry. 9 units (3-0-6); *third term.* *Prerequisites:* Ge 140a or equivalent. For course description, see Geological and Planetary Sciences.

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

Ge/ESE 150. Planetary Atmospheres. 9 units (3-0-6). For course description, see Geological and Planetary Sciences.

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

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

Ge/EE/ESE 157 c. Remote Sensing for Environmental and Geological Applications. 9 units (3-3-3). For course description, see Geological and Planetary Sciences.

ESE/ChE 158. Aerosol Physics and Chemistry. 9 units (3-0-6); *third 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. Given in alternate years; not offered 2015-16.

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. Given in alternate years; not offered 2015-16.

Ge/ESE 170. Microbial Ecology. 9 units (3-2-4); *third term.* 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 2015-16.

ESE/Ch 175. Physical Inorganic Chemistry of Natural Waters. 9 units (3-0-6); second term. *Prerequisites:* Ch 1 or instructor's permission. This course will cover selected aspects of the chemistry of natural and engineered aquatic systems. Lectures cover basic principles of physical-organic and physical-inorganic chemistry relevant to the aquatic environment under realistic conditions. Specific topics that are covered include the principles of equilibrium chemistry in natural water, acid-base chemistry of inorganic and organic acids including aquated carbon dioxide, metal-ligand chemistry, ligand substitution kinetics, kinetics and mechanisms of organic and inorganic redox reactions, photochemical transformations of chemical compounds, biochemical transformations of chemical compounds in water and sediments, heterogeneous surface reactions and catalysis. Thermodynamic, transport, kinetics and reaction mechanisms are emphasized. The primary emphasis during the winter term course will be on the inorganic chemistry of natural waters. Instructors: Hoffmann.

ESE/Ch 176. Physical Organic Chemistry of Natural Waters. 9 units (3-0-6); third term. This course will cover selected aspects of the chemistry of natural and engineered aquatic systems. Lectures cover basic principles of physical-organic and physical-inorganic chemistry relevant to the aquatic environment under realistic conditions. Specific topics that are covered include the principles of equilibrium chemistry in natural water, acid-base chemistry of inorganic and organic acids including aquated carbon dioxide, metal-ligand chemistry, ligand substitution kinetics, kinetics and mechanisms of organic and inorganic redox reactions, photochemical transformations of chemical compounds, biochemical transformations of chemical compounds in water and sediments, heterogeneous surface reactions and catalysis. Thermodynamic, transport, kinetics and reaction mechanisms are emphasized. The primary emphasis during the spring term course will be on the organic chemistry of natural waters emphasizing the fate and behavior of organic compounds and persistent organic pollutants in the global environment. Instructors: Hoffmann.

ESE 200. Advanced Topics in Environmental Science and Engineering. Units by arrangement; any term. Course on contemporary topics in

environmental science and engineering. Topics covered vary from year to year, depending on the interests of the students and staff.

Ge/Bi/ESE 246. Molecular Geobiology Seminar. *6 units (2-0-4).* 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, Geological and Planetary Sciences, Economics, and Social Science.

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 2015–16.

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.

F 104. French Cinema. *9 units (3-0-6); first term.* For description, see L 104.

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 132. Nations/Cultures on Film: Japan. *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.

En/F 161. The New Hollywood. 9 units (3-0-6); *second term*. For course description, see English.

FRESHMAN SEMINARS

FS 2. Freshman Seminar: The Origins of Ideas. 6 units (2-0-4); *second term*. Why do we have 60 minutes in an hour? Why do we use a fork or chopsticks when we eat? Why do we have music? Why do we have sports? The goal of the class is to learn how to enjoy ignorance, be curious and try and discover the origin and the evolutionary processes that led to the ideas and artifacts that are a part of our life. The class is collaborative and interactive: You will teach as much as you will learn - you will learn as much as you will teach. Most importantly, you will realize the fun in discovery and the joy of human interaction. *Freshmen only; limited enrollment*. Instructors: Bruck.

FS/Ay 3. Freshman Seminar: Automating Discovering the Universe. 6 units (2-0-4); *second term*. Powerful new instruments enable astronomers to collect huge volumes of data on billions of objects. As a result, astronomy is changing dramatically: by the end of this decade, most astronomers will probably be analysing data collected in large surveys, and only a few will still be visiting observatories to collect their own data. The tool chest of future astronomers will involve facility with “big data”, developing clever queries, algorithms (some based on machine learning) and statistics, and combining multiple databases. This course will introduce students to some of these tools. After “recovering” known objects, students will be unleashed to make their own astronomical discoveries in new data sets. Limited enrollment. Instructors: Kulkarni.

FS/Ph 4. Freshman Seminar: Astrophysics and Cosmology with Open Data. 6 units (3-0-3); *first term*. Astrophysics and cosmology are in the midst of a golden age of science-rich observations from incredibly powerful telescopes of various kinds. The data from these instruments are often freely available on the web. Anyone can do things like study x-rays from pulsars in our galaxy or gamma rays from distant galaxies using data from Swift and Fermi; discover planets eclipsing nearby stars using data from Kepler; measure the expansion of the universe using supernovae data; study the cosmic microwave background with data from Planck; find gravitational waves from binary black hole mergers using data from LIGO; and study the clustering of galaxies using Hubble data. We will explore some of these data sets and the science that can be extracted from them. A primary goal of this class is to develop skills in scientific computing and visualization - bring your laptop! Not offered 2015-16.

FS/Ph 9. Freshman Seminar: The Science of Music. 6 units (2-0-4); *first term.* This course will focus on the physics of sound, how musical instruments make it, and how we hear it, including readings, discussions, demonstrations, and student observations using sound analysis software. In parallel we will consider what differentiates music from other sounds, and its role psychically and culturally. Students will do a final project of their choice and design, with possibilities including a book review, analysis of recordings of actual musical instruments, or instrument construction and analysis. *Freshmen only; limited enrollment.* Instructor: Politzer.

FS/Ph 11 abc. Freshman Seminar: Research Tutorial. 6 units (2-0-4); *second, 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 freshman and sophomore years will be automatic for those students making satisfactory progress. Graded pass/fail. *Freshmen only; limited enrollment.* Instructor: Phillips.

FS/Ma 12. Freshman Seminar: The Mathematics of Enzyme Kinetics. (2-0-4); *third term. Prerequisites: Ma 1a, b.* Enzymes are at the heart of biochemistry. We will begin with a down to earth discussion of how, as catalysts, they are used to convert substrate to product. Then we will model their activity by using explicit equations. Under ideal conditions, their dynamics are described by a system of first order differential equations. The difficulty will be seen to stem from them being non-linear. However, under a steady state hypothesis, they reduce to a simpler equation, whose solution can describe the late time behavior. The students will apply it to some specially chosen, real examples. Not offered 2015-16.

FS/Bi 13. Freshman Seminar: In Search of Memory. 6 units (2-0-4); *first term.* An exploration of brain function based on weekly readings in an autobiographical account by a Nobel Prize winning neurobiologist. No lectures. Each week there will be reading from chapters of the book plus relevant research papers, discussing trail-blazing neuroscience experiments. Instructor: Pine.

FS/Ph 15. Freshman Seminar: Dance of the Photons. 6 units (2-0-4); *second term.* An exploration of experimental Quantum Mechanics from the beginnings to the future, based on weekly readings and class discussion from the book "Dance of the Photons" by Anton Zeilinger, plus other supplementary sources. No lectures. Interferometers, entanglement, teleportation, quantum computation, and other mysteries will be explored. Not Offered in 2015-16.

FS/Ge 16. Freshman Seminar: Earthquakes. 6 units (2-0-4); *first term.* Earthquakes and volcanic eruptions constitute some of the world's major natural hazards. What is the science behind prediction and/or rapid response to these events? We will review the current understanding of the

science, the efforts that have been made in earthquake and volcano forecasting, and real-time response to these events. We will learn about advances in earthquake preparation in Southern California, and volcanic eruption forecasting and hazard mitigation elsewhere. There is a required field trip to visit faults and volcanoes somewhere in southern California. *Freshmen only; limited enrollment.* Instructor: Stock.

FS 17. Freshman Seminar: The Business Side of Sports. 6 units (2-0-4); second term. Ken Lewis's *Moneyball* (2003) attributes the remarkable success of the low-budget Oakland A's in competing against teams with much larger payrolls to their ability to exploit market failure. The purpose of this course is to evaluate the central claims of the *Moneyball* thesis. Students will read *Moneyball*, many of the classic essays published by Bill James in the *Baseball Abstract*, and some of the classic works in decision theory. The course will necessarily focus on the way baseball executives evaluate both highly quantitative and highly subjective information. Freshmen only; limited enrollment. Instructors: Kiewiet and Claire.

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 planetary 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: Asimow. *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. Instructor: Clayton.

Ge 11 a. Introduction to Earth and Planetary Sciences: Earth as a Planet. 9 units (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. Although Ge 11 abcd is designed as a sequence, any one term may be taken as a standalone course. Instructor: Farley.

Ge 11 b. Introduction to Earth and Planetary Sciences: Earth and the Biosphere. 9 units (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. Although Ge 11 abcd is designed as a sequence, any one term may be taken as a standalone course. Biologists are particularly welcome. Instructors: Fischer, Kirschvink.

Ge/Ay 11 c. Introduction to Earth and Planetary Sciences: Planetary Sciences. 9 units (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 dynamical and chemical processes of planetary systems. Although Ge 11 abcd is designed as a sequence, any one term may be taken as a standalone course. Physicists and astronomers are particularly welcome. Instructor: Brown

Ge 11 d. Introduction to Earth and Planetary Sciences: 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. Although Ge 11 abcd is designed as a sequence, any one term can be taken as a standalone course. Instructors: Clayton, Gurnis.

FS/Ge 16. Freshman Seminar: Earthquakes. 6 units (2-0-4); first term. For course description, see Freshman Seminar.

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 101. Introduction to Geology and Geochemistry. 9 units (3-0-6); first term. Prerequisites: 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: Farley.

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. Instructors: Clayton, Gurnis.

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: Brown.

Ge 104. Introduction to Geobiology. 9 units (3-0-6); second 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; phylogenetic techniques; microbial and molecular evolution. Instructors: Fischer, Kirschvink.

Bi/Ge/ESE 105. Evolution. 12 units (3-4-5); second term. Prerequisites: Completion of Core Curriculum Courses. Prerequisites: Completion of Core Curriculum Courses. For course description, see Biology.

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: Brown.

Ge 109. Oral Presentation. 5 units (2-0-3); 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, Rossman.

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). Not offered 2015-16.

Ge 111 ab. Applied Geophysics Seminar and Field Course. 6 units (3-3-0); second term. Prerequisite: instructor's permission. 9 units (0-3-6); spring break, third term. Prerequisite: Ge 111 a. 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.

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. Given in alternate years; offered 2015-16.

Ge 114 a. Mineralogy. 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.

Ge 114 b. Mineralogy Laboratory. 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 a. Petrology and Petrography: Igneous Petrology. 9 units (3-3-3); second term. *Prerequisites:* Ge 114 ab. Study of the origin, occurrence, tectonic significance and evolution of igneous rocks with emphasis on use of phase equilibria and geochemistry. Given in alternate years; offered 2015-16. Instructors: Stolper.

Ge 115 b. Petrology and Petrography: Metamorphic Petrology. 9 units (3-3-3); second term. *Prerequisites:* Ge 114 ab. 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. May be taken before Ge 115 a. Given in alternate years; not offered 2015-16.

Ge 116. Analytical Techniques Laboratory. 9 units (1-4-4); second term. *Prerequisites:* Ge 114 a or instructor's permission. 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 powder 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.

Ge/Ay 117. Statistics and Data Analysis. 9 units (3-0-6); second term. *Prerequisites:* CS 1 and instructors permission. In modern fields of planetary science and 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 and planetary science 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. Not offered 2015-16.

Ge/ESE 118. Methods in Data Analysis. 9 units (3-0-6); first term. *Prerequisites:* Ma 1 or equivalent. Introduction to methods in data analysis. Course

will be an overview of different ways that one can quantitatively analyze data, and will not focus on any one methodology. Topics will include linear regression, least squares inversion, Fourier analysis, principal component analysis, and Bayesian methods. Emphasis will be on both a theoretical understanding of these methods and on practical applications. Exercises will include using numerical software to analyze real data. Instructor: Tsai.

Ge 120 a. Field Geology: Introduction to Field Geology. 6 units (1-5-0); third term. *Prerequisite:* Ge 11 ab, Ge 106 (may be taken concurrently with Ge 106). A comprehensive introduction to methods of geological field mapping through laboratory exercises in preparation for summer field camp. Laboratory exercises introduce geometrical and graphical techniques in the analysis of geologic maps. Field trips introduce methods of geological mapping. Instructor: Wernicke.

Ge 120 b. Field Geology: 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. Instructor: Wernicke.

Ge 121 abc. Advanced Field Geology. 12 units (0-9-3); first, second, third terms. *Prerequisites:* 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, or sedimentary rocks or geomorphology. Multiple terms of 121 may be taken more than once for credit if taught by different instructors. Instructors: Lamb (a), Grotzinger (b), Stock (c).

Ge 122 abc. Field Geology Seminar. 6 (1-3-2); first, second, or third term. *Prerequisites:* Ge 11ab or Ge 101, or instructor's permission. Each term, a different field topic in Southern California will be examined in both seminar and field format. Relevant readings will be discussed in a weekly class meeting. During the 3-day weekend field trip we will examine field localities relevant to the topic, to permit detailed discussion of the observations. Fall term 2015 topic: cataclastic fault rocks, mylonites and pseudotachylytes. Class can be taken more than once because the content is different each time. Graded pass/fail. Instructor: Stock.

Ge 124 a. Paleomagnetism and Magnetostratigraphy. 6 units (0-0-6); third term. Application of paleomagnetism to the solution of problems in stratigraphic correlation and to the construction of a high-precision geological timescale. A field trip to the southwest United States or Mexico to study the physical stratigraphy and magnetic zonation, followed by lab analysis. Given in alternate years; not offered 2015-16.

Ge 124 b. Paleomagnetism and Magnetostratigraphy 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 paleomagnet-

ic techniques to the determination of the history of the geomagnetic field. Given in alternate years; not offered 2015–16.

Ge 125. Geomorphology. 12 units (3–5–4); first term. *Prerequisite:* Ge 11 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. Given in alternate years; not offered 2015–16.

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.

Ge/Ch 127. Nuclear Chemistry. 9 units (3–0–6); first 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. Given in alternate years; offered 2015–16. Instructor: Burnett.

Ge/Ch 128. Cosmochemistry. 9 units (3–0–6); third term. *Prerequisites:* 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 that may contribute to habitability. 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. Given in alternate years; not offered 2015–16.

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); first term. Prerequisite: instructor's permission. Fundamental aspects of atomic and molecular spectra that enable one to infer physical conditions in astronomical, planetary, and terrestrial environments. Topics will include the structure and spectra of atoms, molecules, and solids; transition probabilities; photoionization and recombination; collisional processes; gas-phase chemical reactions; and isotopic fractionation. Each topic will be illustrated with applications in astronomy and planetary sciences, ranging from planetary atmospheres and dense interstellar clouds to the early universe. Given in alternate years; not offered 2015–16.

Ge/Ay 133. The Formation and Evolution of Planetary Systems. 9 units (3-0-6); third 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: Knutson.

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); second term. Prerequisites: Ph 106 abc, ACM 95/100 ab. A quantitative review of dynamical processes that characterize long-term evolution of planetary systems. An understanding of orbit-orbit resonances, spin-orbit resonances, secular exchange of angular momentum and the onset of chaos will be developed within the framework of Hamiltonian perturbation theory. Additionally, dissipative effects associated with tidal and planet-disk interactions will be considered. Not offered 2015–16.

Ge/ESE 139. Introduction to Atmospheric Radiation. 9 units (3-0-6); third term. 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 examples of applications to climate and remote sensing of Earth, planets and exoplanets. Given in alternate years; offered 2015–16. Instructor: Yung

Ge 140 a. Stable Isotope Geochemistry. 9 units (3-0-6); second term. An introduction to the principles and applications of stable isotope systems to earth science, emphasizing the physical, chemical and biological processes responsible for isotopic fractionation, and their underlying chemical-physics principles. Topics include the kinetic theory of gases and related isotopic fractionations, relevant subjects in quantum mechanics and statistical thermodynamics, equations of motion of charged particles in electrical and magnetic fields (the basis of mass spectrometry), the photochemistry of

isotopic species, and applications to the earth, environmental and planetary sciences. Taught in odd years; alternates with Ge 140b. Not offered 2015–16.

Ge 140 b. Radiogenic Isotope Geochemistry. 9 units (3–0–6); second term.

An introduction to the principles and applications of radiogenic isotope systems in earth science. Topics to be covered include radioactive decay phenomena, geochronometry, isotopes as tracers of solar system and planetary evolution, extinct radioactivities, and cosmogenic isotopes. Instructor: Farley. Taught in even years; alternates with Ge 140a. Offered 2015–16.

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 CO₂ 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 Formation. Given in alternate years; not offered 2015–16.

Ge 145. Isotope-Ratio Mass Spectrometry. 9 units (1–4–4); first term. This class provides a hands-on introduction to the construction and operating principles of instrumentation used for isotope-ratio mass spectrometry. The class is structured as a 1-hour lecture plus 4-hour lab each week examining the major subsystems of an IRMS, including vacuum systems, ionization source, mass analyzer, and detector. Laboratories involve hands-on deconstruction and re-assembly of a retired IRMS instrument to examine its components. Course is limited to 6 students at the discretion of the instructor, with preference given to graduate students using this instrumentation in their research. Instructor: Sessions. Given in alternate years; offered 2015–16.

Ge/ESE 146. Stable Isotope Biogeochemistry. 9 units (3–0–6); third term.

Prerequisites: Ge 140a or equivalent. This course serves as an introduction to the use of stable isotopes in biogeochemistry, and is intended to give interested students the necessary background to understand applications in a variety of fields, from modern carbon cycling to microbial ecology to records of Ancient Earth. Topics include the principles of isotope distribution in reaction networks; isotope effects in enzyme-mediated reactions, and in metabolism and biosynthesis; characteristic fractionations accompanying carbon, nitrogen, and sulfur cycling; and applications of stable isotopes in the biogeosciences. Instructor: Sessions.

Ge/ESE 149. Marine Geochemistry. 9 units (3–0–6); third term. *Prerequisite:* ESE 102.

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. Given in alternate years; not offered 2015–16.

Ge/ESE 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. Planetary Surfaces. 9 units (3–3–3); first term. Exogenous (impact cratering, space weathering) and endogenous (tectonic, volcanic, weathering, fluvial, aeolian, and periglacial) processes shape the surfaces of planets. We will review the mechanisms responsible for the formation and modification of the surfaces of solar system bodies, studying both composition and physical processes. Instructor: Ehlmann.

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. Instructor: Adkins.

Ge/ESE 155. Paleoceanography. 9 units (3–0–6); third term. *Prerequisites:* ESE 102. 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; offered 2015–16.

Ge 156. Topics in Planetary Surfaces. 6 units (3–0–3). *Offered by announcement only.* 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.

Ge/EE/ESE 157 c. Remote Sensing for Environmental and Geological Applications. 9 units (3–3–3); third term. Use of different parts of the electromagnetic spectrum (visible, ultraviolet, infrared, and radio wavelengths) for interpretation of physical and chemical characteristics of the surfaces of Earth and other planets. Topics: interaction of light with materials, spectroscopy of minerals and vegetation, atmospheric removal, image analysis, classification, and multi-temporal studies. This course is complementary to EE 157ab with additional emphasis on applications for geological and environmental problems, using data acquired from airborne and orbiting remote

sensing platforms. Students will work with digital remote sensing datasets in the laboratory and there will be one field trip. Instructor: Ehlmann.

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. Given in alternate years; not offered 2015-16.

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 ab 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.

Ge 165. Geophysical Data Analysis. 9 units (3-0-6); third 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 value decomposition. Not offered 2015-16.

Ge 166. Hydrology. 9 units (3-0-6); third term. Prerequisites: Math 1 or equivalent. Introduction to hydrology. Focus will be on how water moves on earth, including in groundwater, rivers, oceans, glaciers, and the atmosphere. Class will be based in fluid mechanics, which will be covered. Specific topics will include the Navier-Stokes equation, Darcy's law, aquifer flow, contaminant transport, turbulent flow, gravity waves, tsunami propagation, geostrophic currents, Ekman transport, glacier flow laws, and the Hadley circulation. Given in alternate years, offered 2015-16. Instructor: Tsai.

Ge 167. Tectonic Geodesy. 9 units (3-0-6); fall term. Prerequisites: a working knowledge of unix/linux or equivalent, linear algebra, and coursework in geophysics. 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. Given in alternate years; offered 2015-16.

Ge 168. Crustal Geophysics. 9 units (3-0-6); first 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. Offered 2015-16.

Ge 169 abcd. Readings in Geophysics. 6 units (3-0-3); first, second, third, fourth 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. Prerequisites: Either ESE/Bi 166 or ESE/Bi 168. 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. Offered in alternate years, not offered 2015-16.

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.

CE/ME/Ge 173. Mechanics of Soils. 9 units (3-0-6); second term. For course description, see Civil Engineering.

ME/CE/Ge 174. Mechanics of Rocks. 9 units (3-0-6); third term. For course description, see Mechanical Engineering.

Ge 177. Active Tectonics. 12 units (3-3-6); third 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.

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. Instructors: 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 planetary sciences. Students may enroll for any or all terms of the course without regard to sequence. Instructor: Staff.

Ge 195. Special Topics in Field Geology. *Units to be arranged. Offered by announcement.* 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 197. Special Topics in Geobiology. *Units to be arranged. Offered by announcement only.* Advanced-level discussions of problems of current interest

in the geobiological sciences. Students may enroll for any or all terms of the course without regard to sequence. Instructor: Staff.

Ay/Ge 198. Special Topics in the Planetary Sciences. 9 units (3-0-6); third term. For course description, see Astrophysics.

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); first 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 2015-16.

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. Given in alternate years; not offered 2015-16.

Ge 215. Topics in Advanced Petrology. 12 units (4-0-8); first 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. Given in alternate years; not offered 2015-16.

Ge 217. Radiogenic Isotopes Seminar. 6 units (3-0-3); second term. Prerequisite: Ge 140 or permission of instructor. The course deals with advanced topics in radiogenic isotope geochemistry and builds on Ge 140, addressing unconventional applications of radioisotopes as well as treating several conventional radiogenic systems in more detail. Each unit begins with a lecture on the history of the system followed by guided discussion of cur-

rent developments. Special topics include the history of radiogenic isotope geochemistry at Caltech, U-series dating of sediments, high precision U-Pb and $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology, and heavy noble gases. Given in alternate years; not offered 2015–16.

Ge 218. Stable Isotopes Seminar. 6 units (3–0–3); second term. *Prerequisites:* Ge 140 or permission of instructor. The course deals with advanced topics in stable isotope geochemistry and builds on Ge 140. The course will explore in depth the theory and applications of a subject in stable isotope geochemistry, selected by consensus of the enrolled students at or before the beginning of term. Example subjects could include: stable isotope thermometry; paleoclimate studies; paleoaltimetry; the early solar system; terrestrial weathering; photochemistry; or biosynthetic fractionations. The class will read and discuss classic papers in that subject area, supplemented with instructor lectures and broader background reading. All participants will lead discussions of papers and present one lecture on a relevant subject. Instructor: Eiler. Given in alternate years; offered 2015–2016.

CE/Ge/ME 222. Earthquake Source Processes, Debris Flows, and Soil Liquefaction: Physics-based Modeling of Failure in Granular Media. 6 units (2–0–4); third term. For course description, see Civil Engineering.

Ge 232. Chemistry of the Solar System. 9 units (3–0–6); first term. *Prerequisites:* instructor's permission. The isotopic and elemental compositions of extraterrestrial materials provide clues to conditions, events, and processes during the formation of the solar system. Specific topics include: solar elemental and isotopic compositions; chronology from short-lived nuclei; the unique role of volatile elements; pre-solar grains from meteorites; chondritic meteorite components as clues to solar nebula and asteroid evolution; interplanetary and comet coma dust; asteroidal igneous rocks; overview of lunar materials. Given in alternate years; not offered 2015–16.

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/ESE 246. Molecular Geobiology Seminar. 6 units (2–0–4); third 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.

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. Given in alternate years; not offered 2015-16.

ME/Ge/Ae 266 ab. Dynamic Fracture and Frictional Faulting. 9 units (3-0-6). For course description, see Mechanical Engineering.

Ge 270. Continental Tectonics. 9 units (3-0-6); third 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; offered 2015-16.

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 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 a. European Civilization: The Classical and Medieval Worlds. 9 units (3-0-6). For course description, see Humanities.

Hum/H 3 b. European Civilization: Early Modern Europe. 9 units (3-0-6). For course description, see Humanities.

Hum/H 3 c. European Civilization: Modern Europe. 9 units (3-0-6). For course description, see Humanities.

Hum/H 4 a. Civilization, Science, and Archaeology: Before Greece: The Origins of Civilization in Mesopotamia. 9 units (3-0-6). For course description, see Humanities.

Hum/H 4 b. Civilization, Science, and Archaeology: The Development of Science from Babylon through the Renaissance. 9 units (3-0-6). For course description, see Humanities.

Hum/H 4 c. Civilization, Science, and Archaeology: The Origins of Polytheism and Monotheism in Ancient Egypt, Mesopotamia, and Israel and the Nature of Religious Belief. 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.*

Art/H 68. Modern Art. 9 units (3-0-6); *first term.* For course description, see Art.

Art/H 69. Modernism in the Visual Arts, 1850-1945. 9 units (3-0-6). For course description, see Art.

E/H/Art 89. New Media Arts in the 20th and 21st Centuries. 9 units (3-0-6). For course description, see Engineering.

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); *second term.* This course is designed to introduce students to the formative period of Western medieval history, roughly from the fourth through the tenth centuries. It will emphasize the development of a new civilization from the fusion of Roman, Germanic, and Christian traditions, with a focus on the Frankish world. The course focuses on the reading, analysis, and discussion of primary sources. Instructor: Brown.

H 108 b. The High Middle Ages. 9 units (3-0-6); *third term.* This course is designed to introduce students to European history between 1000 and 1400. It will provide a topical as well as chronological examination of the

economic, social, political, and religious evolution of western Europe during this period, with a focus on France, Italy, England, and Germany. The course emphasizes the reading, analysis, and discussion of primary sources. Instructor: Brown.

H 109. Medieval Knighthood. *9 units (3-0-6); first 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 2015–16.

H 111. The Medieval Church. *9 units (3-0-6); second term.* 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 2015–16.

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, blood-thirsty 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 2015–16.

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 2015–16.

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. Not offered 2015–16.

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. Not offered 2015–16.

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 anti-globalization movements of today. Not offered 2015–16.

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. Not offered 2015–16.

H/An 123. Anthropological Demography. *9 units (3–0–6); first term.* Birth, death, marriage, and migration are the most basic events in people's lives. These events are shaped by both human biology and cultural contexts. This course combines biological and cultural approaches to the study of human populations. Topics include basic demographic techniques, evolutionary perspectives on human demography, longevity, senescence, kinship, household organization, and nuptiality. Students will explore the roles of culture, ecology, and subsistence in demographic explanation. Emphasis is placed on understanding crosscultural and historical variation in population dynamics. Not offered 2015–16.

H/SS 124. Problems in Historical Demography. *9 units (3–0–6); first term.* Birth, marriage, and death—the most basic events in people's lives—are inextricably linked to larger economic and social phenomena. An under-

standing 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 2015–16.

H 125. Soviet Russia. *9 units (3–0–6); first term.* Why was the Russian Revolution of 1917 successful? And how did the Soviet system survive nearly 75 years? These questions will be addressed in the wider context of Russian history, with a focus on political, economic, and social institutions in the pre- and post-revolutionary period. Subjects covered include the ideological underpinnings of Bolshevism, Lenin and the Bolshevik coup, the rise of Stalin, collectivization, socialist realism, the command economy, World War II, the Krushchev ‘thaw’, dissident culture and the arts, popular culture, and Gorbachev’s perestroika. A variety of sources will be used, including secondary historical literature, fiction, film, and art. Instructor: Dennison.

H 128. Sustainability and Conservation in the Early Modern World. *9 units (3–0–6); first term.* Sustainability—from corporate boardrooms to communes, the term has been the subject of protests, marketing campaigns, and government policies. Scientists, activists, and politicians have proposed new methods for achieving it; however, the history of the term remains murky. In this course, we will explore how early modern people understood and regulated resources to try to uncover examples of sustainable farming, forestry, and industry from the past. Unlike many courses that focus on specific regions, we will reach beyond borders to examine the intersections of the modes of regulation of resources in Asia, Europe, and North America during the early modern period. Instructors: Pluymers.

H 129. Rivers and Human History. *9 units (3–0–6); second term.* For thousands of years, rivers have been central to human history. They have served as crucial sources of food and water, the sites for religious and political ceremonies, and corridors for transportation. Rivers have also flooded, become polluted, and even caught fire. In this course we will explore how human beings around the world have attempted to manage rivers and the people who live alongside them examining topics such as damming, diversion, and flood control. We will conclude by examining the history and future of the Los Angeles River and its tributaries, which, as concretized flood control channels, offer a unique example of the transformative power of engineering. For this section, students will take a field trip to explore the Los Angeles River. Instructors: Pluymers.

H 130. Innovative History. *9 units (3–0–6); second term.* 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 post-modern theorists, which provide intellectual underpinning for experimenting with new forms of history. Not offered 2015–16.

H/F 131. History on Film. *9 units (2–2–5); second 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 2015–16.

H/F 132. Nations/Cultures on Film: Japan. *9 units (2–2–5); third term.* Based upon the premise that a great deal of the history and culture of a nation is inscribed in the dramatic features its film makers produce, the course will each term focus on a single nation and/or culture. Each week there will be a screening, supplemented by appropriate readings dealing with history, culture, and film analysis. During the two hour weekly seminar, students will be expected to discuss the film and the readings, while the instructor will provide additional background material and introduce them to the language of cinema. Possible topics include the United States, Japan, Russia, France, Spain, Germany, and Italy. On occasion the class may deal with particular periods in history (e.g. the Italian Renaissance, Imperial Rome) or with cultures that cross national boundaries, such as the Arab World or Latin America. Students will be expected to write short papers after most screenings and one formal term paper. Not offered 2015–16.

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. Not offered 2015–16.

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. Not offered 2015–16.

H 135. War, Conquest, and Empires. *9 units (3–0–6); second term.* 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. Instructor: Hoffman.

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 2015–16.

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. Not offered 2015–16.

Law/PS/H 148 ab. The Supreme Court in U.S. History. *9 units (3-0-6).* For course description, see Law.

HPS/H 152. Renaissance Anatomy and Botany. *9 units (3-0-6); third term.* For course description, see History and Philosophy of Science.

Art/H 153. The Politics of Representation in American Art, 1935–2000. *9 units (3-0-6); first term.* For course description, see Art History.

Art/H 154. Art and Technology. *9 units (3-0-6); third term.* For course description, see Art History.

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 164. History of Space Exploration. 9 units (3-0-6); *first term*. 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/PI 173. History of Chemistry. 9 units (3-0-6); *second term*. For course description, see History and Philosophy of Science. 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/PI 176. History of Alchemy. 9 units (3-0-6); *third term*. 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 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. See and Tell: 3-D Models for the Visualization of Complex Concepts From the 16th Century to Modern Times. 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 184. Travel, Mobility, Migration. 9 units (3-0-6); *third term*. People, objects, and knowledge in the European Age of Revolutions, 1770-1848. The aim of this course is to examine the movement of peoples, cultural artifacts, and the dissemination of different sorts of knowledge, during and after the Revolutionary upheavals and nationalist struggles of the late eighteenth and early nineteenth centuries. Topics will include nationalism and multi-national communities; political and intellectual exile; imperial ambition, science and knowledge; the effects of warfare on patterns of migration; looting, theft and cultural property. The class will include a number of in-depth case studies, including Italy and South Asia. Not offered 2015-16.

H/HPS 185. Angels and Monsters: Cosmology, Anthropology, and the Ends of the World. 9 units (3-0-6); *first term*. This course explores late medieval European understandings of the origins, structure, and workings of the cosmos in the realms of theology, physics, astronomy, astrology, magic, and medicine. Attention is given to the position of humans as cultural creatures at the intersection of nature and spirit; as well as to the place of Christian Europeans in relation to non-Christians and other categories of outsiders within and beyond Europe. We will examine the knowledge system that anticipated racializing theories in the West. Instructor: Wey-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 187. The Constitution in the Early Republic. 9 units (3-0-6); *first term*. This course will trace many of the major constitutional debates that occurred during the first half-century of U.S. History. We will look to the courts, to the legislatures, to Presidents, and to constitutional theorists of the Early Republic to gain insight into how the first generations of Americans understood their Constitution and the governments and rights it recognized. During this formative period, Americans contemplate the location of sovereignty in a federated republic, the rights and privileges of citizenship, and the role of judicial review in a democratic society. Though we will remain firmly entrenched in the period before the Civil War, we will find that many of the issues that created constitutional strife two centuries ago are still relevant to the constitutional questions of today. Not offered 2015-16.

H 188. Origins of the US Civil War. 9 units (3-0-6); *first term*. The purpose of this course is to investigate the various causes of the US Civil War. Students will be exposed to prevailing interpretations, which rely mostly on national frames of reference when identifying the economic, political, and constitutional causes of the Sectional Crisis and War. Half of the term will be devoted to these themes. Subsequently, we will be spending the second half of the term examining recent scholarship that examines the international factors on the brewing Sectional Crisis, from the ramifications of British Emancipation to the fluctuating global cotton market. During the last week, we will discuss these interpretative differences and identify possible avenues of synthesis. Students will leave the course with a thorough understanding of the causes of the Civil War and an introduction to transnational influences on American historical development. Not offered 2015–16.

H/L 191. Perspectives on History through German Literature. 9 units (3-0-6); *second term*. Industrialization, economic growth, and democracy came to Germany much later than to England and France, and the forms they took in Germany were filtered through the specific institutional character of Central Europe. German-speaking writers and intellectuals saw these trends from the perspective of indigenous intellectual traditions, and the resulting collisions of values and priorities largely shaped European and American social, political, and literary debates for much of the nineteenth and twentieth centuries. This course explores these writings (in English translation) against the historical background of Central European society, focusing on particular works of Goethe, Hoffmann, Heine, Nietzsche, Kafka, Rilke, and Mann. Instructor: Dennison.

H 192. The Crusades. 9 units (3-0-6); *second term*. This course will introduce students to the series of religiously motivated European invasions of the Middle and Near East that began at the end of the eleventh century and that led to the creation of Latin Christian principalities in Palestine. Though the crusading movement came to embroil much of Europe itself, the course will focus strictly on the military expeditions to what the Crusaders called the Holy Land, and the history of the Crusader states up to the point of their destruction at the end of the thirteenth century. The course will be guided by the following questions: how did medieval Christianity justify wars of aggression against foreign peoples and religions? What motivated western Europeans to leave their homes and march into a hostile environment, where they often faced impoverishment if not death and where maintaining a Christian presence was a constant struggle? How did they manage to erect stable political entities in alien territory that lasted as long as they did, and how did they have to adapt their own culture to do so? Finally, how did the native peoples of the regions the Crusaders invaded and conquered—Muslim but also Christian and Jewish—perceive the Crusaders? How did the Crusaders' presence affect life in a region whose populations had their own ancient histories and patterns of life? Not offered 2015–16.

En/H 193. Cervantes, Truth or Dare: Don Quixote in an Age of Empire. 9 units (3-0-6). For course description, see English.

H/HPS 194. Travels, Travelers, and Travel Tales: 1700-1900. 9 units (3-0-6); *third term*. This course explores the different and changing forms of travel and its representations in the 18th and 19th centuries. It will examine travels within Europe, in the Middle East and Asia, in Africa and the Pacific, in order to look at different sorts of travel from varying points of view, including travel as recreation, the collection and interpretation of scientific data, the control of resources, and the epistemological claims that underwrite imperialism. Recent critical writings on travel narrative and travel fiction will supplement historical travel texts and images, which may include the Paris Academy's exploration of Peru, Cook's travels to the Pacific, and Darwin's voyage on the Beagle. Not offered 2015-16.

H 195. Vesuvius and Pompeii: Geology, Archaeology and Antiquity from the Enlightenment to the Present. 9 units (3-0-6); *first term*. This course examines Vesuvius and Pompeii and the relations between them from the earliest Pompeian discoveries to the present debate about the fate of the buried city, and the plans to cope with an impending Vesuvian eruption. It analyses the changing debates about the volcano - and its place in earth sciences - the development of archaeological techniques and their discoveries, the relationship between a tourist economy and the region, and the public debates about how to deal with disasters and conservation in a rapidly changing political environment. Not offered 2015-16.

En/H 197. American Literature and the Technologies of Reading. 9 units (3-0-6); *second term*. For course description, see English.

HPS/H 198. Print In a Global Context, 14th to 19th Centuries. 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 archi-

val 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 Munro 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 2015–16.

HPS 105. Science and Literature. *9 units (3–0–6); second term.* 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 2015–16

HPS/PI 120. Introduction to Philosophy of Science. *9 units (3–0–6); second 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: Eberhardt.

HPS/PI 121. Causation and Explanation. *9 units (3–0–6); second 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. Instructor: Eberhardt.

HPS/PI 122. Probability, Evidence, and Belief. 9 units (3-0-6); second term. Philosophical and conceptual issues arising from the study of probability theory and how it relates to rationality and belief. Topics discussed may include the foundations and interpretations of probability, arguments for and against the view that we ought to have personal degrees of belief, rational change in beliefs over time, and the relationship between probability and traditional epistemological topics like evidence, justification, and knowledge. Not offered 2015-16.

HPS/PI 123. Introduction to the Philosophy of Physics. 9 units (3-0-6); first term. Prerequisites: Ph 1abc or instructor's permission. This course will examine the philosophical foundations of the physical theories covered in the freshman physics sequence: classical mechanics, electromagnetism, and special relativity. Topics may include: the goals of physics; what laws of nature are; the unification of physical theories; symmetries; determinism; locality; the reality of fields; the arrow of time. Instructors: Sebens.

HPS/PI 124. Philosophy of Space and Time. 9 units (3-0-6); first term. 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 2015-16.

HPS/PI 125. Philosophical Issues in Quantum Physics. 9 units (3-0-6); third term. Prerequisites: Ph 2b or Ph 12b. This course will focus on philosophical and foundational questions raised by quantum physics. Questions may include: Is quantum mechanics a local theory? Is the theory deterministic or indeterministic? What is the role of measurement and observation? Does the wave function always obey the Schrödinger equation? Does the wave function give a complete description of the state of a system? Are there parallel universes? How are we to understand quantum probabilities? Instructors: Sebens.

HPS/PI 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. Not offered 2015-16.

HPS/PI 129. Introduction to Philosophy of Biology. 9 units (3-0-6); first term. 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, reduction-

ism, teleological and functional reasoning, and ethical issues arising from contemporary biological research. Not offered 2015–16.

HPS/PI 130. Philosophy and Biology. 9 units (3-0-6); *second term*. A selection of philosophical issues arising in the biological sciences. Topics will vary by term. Not offered 2015–16.

HPS/PI 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 2015–16.

HPS/PI 134. Current Issues in Philosophical Psychology. 9 units (3-0-6); *first term*. 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. Instructor: Cowie.

HPS/PI 135. Moral Philosophy and the Brain. 9 units (3-0-6); *first term*. This course will examine the impact of recent advances in neuroscience on moral philosophy. Topics to be addressed include: the evolution of morality and a naturalistic perspective on ethics; the role of brain imaging in adjudicating between deontological vs. consequentialist perspectives on moral decision-making and judgment; the relation between virtue theory and habit systems in the brain; brain imaging of altruism and its implications for egoism, empathy, and moral motivation; moral agency and free will; the neuroscience of distributive justice; the debate regarding the normative significance of neuroscience for moral philosophy. Not offered 2015–16.

HPS/PI 136. Happiness and the Good Life. 9 units (3-0-6); *third term*. This course will critically examine the emerging science of happiness and positive psychology, its philosophical assumptions, methodology, and its role in framing social policy and practice. Topics to be addressed include: the relation between happiness as subjective well-being or life satisfaction and philosophical visions of the good life; the relation between happiness and virtue; the causes of happiness and the role of life experience; happiness and economic notions of human welfare, attempts to measure happiness, and the prospect for an economics of happiness; happiness as a brain state and whether brain science can illuminate the nature of happiness; mental illness and psychiatry in light of positive psychology. Instructors: Quartz.

HPS/PI 138. Human Nature and Society. 9 units (3-0-6); *second term*. 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. Instructor: Quartz.

HPS/H 152. Renaissance Anatomy and Botany. 9 units (3-0-6); third term. In this class, “the Renaissance” refers to a cultural movement taking place between roughly 1500 and the early decades of the seventeenth century, where anatomy and botany, and those who studied medicine and natural history, formed a part of this movement. Through lectures, class discussion, videos, and field trips to see books, plants, and art work discussed in class, students will learn about the persistence of ancient forms of knowledge, the relations between art and science, the discovery of the circulation of the blood, the expanding use of physiological experiments, and the rise of a mechanistic understanding of the body during the Renaissance. Instructors: Manning.

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. Not offered 2015–16.

HPS 157. The Evolution of Knowledge. 9 units (3-0-6); second term. The course analyzes the history of science from a new perspective, that of an evolution of knowledge. It begins with a discussion of the cognitive, social, and material dimensions of knowledge, introducing basic concepts from cognitive science and sociology. It analyzes current discussions of cultural evolution and their relevance to understanding the history of science. Building on this theoretical introduction, major milestones are reviewed, the origin of science in antiquity, the Scientific Revolution of the early modern period, and the transition from classical to modern science, relying on secondary literature as well as on primary sources. Instructors: Renn.

HPS/H 158. The Scientific Revolution. 9 units (3-0-6); third 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 2015–16.

HPS/H 159. The Cold War and American Science. 9 units (3-0-6); second term. 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 2015–16.

HPS/H 160 ab. Einstein and His Generation: The History of Modern Physical Sciences. 9 units (3-0-6); *third term*. 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. Instructor: Kormos-Buchwald.

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. Instructor: Feingold.

HPS/H 164. History of Space Exploration. 9 units (3-0-6); *first term*. This course will cover the entire history of space exploration with a particular focus on the Cold War era. The course will begin with the first dreaming about space travel during the 16th century and end with the rise of new space powers such as China and India. We will consider the political, military, technological, social, and cultural dimensions of space exploration. Topics covered include speculations on why humans were drawn to the cosmos in the first place, the weaponization of space, the popular culture of TV shows (such as *Star Trek*) and movies (such as the *Alien* series), the secret Soviet space program, the extraordinary Apollo missions to the Moon, and the International Space Station of the 21st century. Instructors: Siddiqi.

HPS/PI 165. Selected Topics in Philosophy of Science. 9 units (3-0-6); offered by announcement. Instructors: Staff, visiting lecturers.

HPS/H 166. Historical Perspectives on the Relations between Science and Religion. 9 units (3-0-6); *second 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: Feingold.

HPS/H 167. Experimenting with History/Historic Experiment. 9 units (3-0-6); *second, third terms*. 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: Buchwald, J.

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 2015–16.

HPS/H 169. Selected Topics in the History of Science and Technology. 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. Not offered 2015–16.

HPS/H 171. History of Mechanics from Galileo through Euler. 9 units (3-0-6); second, third terms. 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 2015–16.

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 2015–16.

HPS/H/PI 173. History of Chemistry. 9 units (3-0-6); second term. This course examines developments in chemistry from medieval alchemy to the time of Lavoisier and Dalton. 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 2015–16.

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 2015–16.

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 2015–16.

HPS/H/PI 176. History of Alchemy. 9 units (3–0–6); third term. Alchemy, long considered one of history's "losers," has recently acquired a new and very different prominence among historians as a forerunner of experimental science in general and of chemistry in particular. This course surveys the field of alchemy over its main period of development, considering cases from the ancient world, medieval Islam and Christendom, and early modern Europe. The goal is to chart the evolution of alchemical theory and practice from its inception until the period of its decline at the end of the seventeenth century. Not offered 2015–16.

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 2015–16.

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 2015–16.

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 2015–16.

HPS/H 182. See and Tell: 3-D Models for the Visualization of Complex Concepts from the 16th century to modern times. 9 units (3-0-6); *first term*. 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 2015–16.

PI/HPS 183. Bioethics. 9 units (3-0-6); *offered by announcement*. For course description, see Philosophy.

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); *third 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 fundamental 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. Not offered 2015–16.

HPS/PI 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. Not offered 2015–16.

H/HPS 194. Travels, Travelers, and Travel Tales: 1700-1900. 9 units. For course description, see History.

HPS/H 196. Science in Popular Culture. 9 units (3-0-6); third term. This course will be a historical survey of the intersection between science and popular culture. As such, our goal will be to explore and understand popular science as a historical phenomenon. The course will trace the evolution of popular science in the Western world through important transformations in the modern era, beginning with the rise of a distinct category of “popular science” during the Victorian Era and then moving through to the present day. During the term, we will study a variety of popular scientific forms, such as science fiction, magazines, comics, graphic novels, sci-fi movies, and TV shows. Students will be required to engage in critical analysis of all the assigned readings and actively participate in an online blog. Instructors: Siddiqi.

HPS/H 198. Print In a Global Context, 14th to 19th Centuries. 9 units (3-0-6); third term. New types of media came into being during the 14th and 15th centuries, leading eventually to a revolution of communication from the 16th century, with the coming of the printing press. This course offers an advanced approach to the variety and power of media, by following text culture in a global perspective before and after the introduction of the printing press by Johannes Gutenberg in the second half of the 15th century. Important issues concern the role of paper, the techniques of producing books and newspapers or pamphlets, the function of illustrations, and finally practices of selling, reading and manipulating information all over the world. The course covers print cultures in Asia, The Ottoman Empire, the Mediterranean, Northern Europe, and the Atlantic World. Not offered 2015–16.

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 2015–16.

Hum/H 2. American History. 9 units (3-0-6); offered by announcement. Among the major events, trends, and problems of our country’s history are the American Revolution, the framing and development of the Constitution, wars, slavery and emancipation, ethnic and gender relations, immigration, urbanization, westward conquest, economic fluctuations, changes in the sizes and functions of governments, foreign relations, class conflicts, domestic violence, and social and political movements. Although no one course can treat all of these themes, each freshman American history course will deal with two or more of them. How have American historians approached them? What arguments and evidence have scholars offered for their interpretations and how can we choose between them? In a word, what can we know about our heritage? Instructor: Kousser.

Hum/H 3 a. European Civilization: The Classical and Medieval Worlds. 9 units (3-0-6); offered by announcement. 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. Instructor: Brown.

Hum/H 3 b. European Civilization: Early Modern Europe. 9 units (3-0-6); offered by announcement. 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: Wey-Gomez, Hoffman.

Hum/H 3 c. European Civilization: Modern Europe. 9 units (3-0-6); offered by announcement. 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, Dennison.

Hum/H 4 a. Civilization, Science, and Archaeology: Before Greece: The Origins of Civilization in Mesopotamia. 9 units (3-0-6); offered by announcement. 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. Not offered 2015-16.

Hum/H 4 b. Civilization, Science, and Archaeology: The Development of Science from Babylon through the Renaissance. 9 units (3-0-6); offered by announcement. 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. Instructor: Buchwald, J.

Hum/H 4 c. Civilization, Science, and Archaeology: The Origins of Polytheism and Monotheism in Ancient Egypt, Mesopotamia, and Israel and the Nature of Religious Belief. 9 units (3-0-6); offered by announcement. 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. Not offered 2015-16.

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, Pigman, Jahner, Saltzman.

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: Hunter, Weinstein, Jurca.

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, Gilmore.

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 *Nicomachean 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: Cowie, Quartz.

Hum/PI 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: Hitchcock, Eberhardt, Sebens.

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. Instructor: Feingold.

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 2015–16.

F/Hum 32. Humanities on Film. 3 units (1-1-1). For course description, see Film.

Hum 105 ab. Topics in French Culture and Literature. 9 units (3-0-6); second term. For description, see L 105 ab.

Hum 114 abc. Spanish and Latin American Literature. 9 units (3-0-6); first, second, third terms. For description, see L 114 abc.

Hum 119. Selected Topics in Humanities. 9 units (3-0-6); offered by announcement. Instructors: Staff, visitors.

L/Hum 152 ab. French Literature in Translation: Classical and Modern. 9 units (3-0-6); third term. For course description, see Languages.

L/Hum 162. Spanish and Latin American Literature in Translation. 9 units (3-0-6); For course description, see Languages.

Hum 174. Topics in Chinese Literature. 9 units (3-0-6); third term. For description, see L 174.

INTERDISCIPLINARY STUDIES PROGRAM

Students who have chosen to enter the Interdisciplinary 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 pages 275–276 for complete details.

INFORMATION SCIENCE AND TECHNOLOGY

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. Freshmen only; limited enrollment.* Instructor: Bruck.

LANGUAGES

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 2015–16.

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.* *Prerequisites:* 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. Instructors: Orcel, Merrill.

L 104. French Cinema. 9 units (3-0-6); *first term. Offered concurrently with F 104.* *Prerequisites:* 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, Carne, 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. Students who write papers in English may enroll in this class as F 104, which satisfies the advanced humanities requirement. Not offered 2015-16.

L 105 ab. Topics in French Culture and Literature. 9 units (3-0-6); *second term.* Offered concurrently with Hum 105 ab. L 105 a and L 105 b taught in alternate years. *Prerequisites:* L 103 abc or equivalent. Part a: 20th-century French literature. Part b: Contemporary France. Conducted in French. Students who write papers in English may enroll in this class as Hum 105 ab, which satisfies the advanced humanities requirement. Instructors: Orcel.

L 106 abc. Elementary Japanese. 9 units (5-0-4); *first, second, third terms.* *Prerequisites:* Section a is required for sections b and c. Emphasis on oral-aural skills, and understanding of basic grammar. Immediate introduction of the native script – hiragana, katakana – and gradual introduction to 300 to 500 characters. Instructor: Hirai.

L 107 abc. Intermediate Japanese. 10 units (5-1-4); *first, second, 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. Rec-

ognition 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: Orצל.

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. Instructor: Arjona, Garcia.

L 114 abc. Spanish and Latin American Literature. 9 units (3-0-6); *first, second, third terms.* Offered concurrently with Hum 114 abc. Prerequisites: 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. Students who write papers in English may enroll in this class as Hum 114 abc, which satisfies the advanced humanities requirement. Instructors: Garcia, Arjona.

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 2015–16.

H/Lit 142. Perspectives on History through Russian Literature. 9 units (3-0-6). For course description, see History.

L/Hum 152 ab. French Literature in Translation: Classical and Modern. 9 units (3-0-6); *third term.* 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. Instructors: Merrill.

L/Hum 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.

L 167 abc. Latin Literature. 9 units (3-0-6); *second, 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. Offered concurrently with Hum 174. Prerequisites: 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. Students who write papers in English may enroll in this class as Hum 174, which satisfies the advanced humanities requirement. Instructors: Ming.

L 175. French Conversation. 6 units (3-0-3); third term. Prerequisites: L 102 abc and L 103 abc or equivalent. Intense training in oral expression, pronunciation, vocabulary, listening comprehension and fluency. The class is designed for students planning to attend Ecole Polytechnique. Discussion materials and guest lectures will focus on technical language to prepare students for their classes in math and science. Taught in French. Enrollment limited to 12. L 175 can be repeated for credit since the content is never the same (different speakers, different articles discussed in class) Instructor: Orcel

H/L 191. Perspectives on History through German Literature. 9 units (3-0-6); For course description, see History.

LAW

Law 33. Introduction to Law and Law and Economics. 9 units (3-0-6). An introduction to Anglo-American law from both the legal and the social- scientific points of view. Subject can vary from year to year. Available for introductory social science credit. Not offered 2015-16.

PI/Law 99. Causation and Responsibility. 9 units (3-0-6). For course description, see Philosophy. Not offered 2015-16.

Law 134. Law and Technology. 9 units (3-0-6). 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 particular scientific areas in depth (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 helpful. Graded written work includes two problem sets, a midterm and a final using essay and short answer formats. Not offered 2015–16.

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 2015–16.

Law 136. Tax Law and the Democratic State. 9 units (3–0–6); second term.

Prerequisites: Ec 11 or PS12. An introduction to the role of tax in society. This course provides an overview of the U.S. tax system and the historical and political factors that influenced its development. This course will examine several key legal concepts that shape the federal income tax system as well as issues related to democracy and taxation, tax and inequality, tax and economic growth, and tax and globalization. It will also look at current tax reform proposals. Each student will be expected to complete three essays during the quarter. Not offered 2015–16.

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.

APh/MS 105 abc. States of Matter. 9 units (3-0-6); first, second, third terms. For course description, see Applied Physics.

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: Staff.

MS 115. Fundamentals of Materials Science. 9 units (3-0-6); first term. *Prerequisites:* 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. The relationships between chemical bonding, crystal structure, thermodynamics, phase equilibria, microstructure, and properties are described. Instructors: Faber.

MS/ME/MedE 116. Mechanical Behavior of Materials. 9 units (3-0-6); second 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.

MS/APh 122. Diffraction, Imaging, and Structure. 9 units (0-4-5); second and third terms. *Prerequisites:* MS 132, may be taken concurrently. Experimental methods in transmission electron microscopy of inorganic materials including diffraction, spectroscopy, conventional imaging, high resolution imaging and sample preparation. Weekly laboratory exercises to complement material in MS 132. Instructors: Staff.

MS 125. Advanced Transmission Electron Microscopy. 9 units (1-6-2); third term. *Prerequisite:* MS 122. Diffraction contrast analysis of crystalline defects. Phase contrast imaging. Physical optics approach to dynamical electron diffraction and imaging. Microbeam methods for diffraction and

imaging. Chemical analysis by energy dispersive X-ray spectrometry and electron energy loss spectrometry. Instructor: Ahn.

MS 131. Structure and Bonding in Materials. 9 units (3–0–6); second term. *Prerequisites:* graduate standing or introductory quantum mechanics. Electronic structure and orbitals in atoms. Structure and symmetry of crystals. Reciprocal space and Brillouin zone. Born-Oppenheimer approximation. Bloch states and band theory. Tight binding and plane-waves. Lattice vibrations and lattice waves. Total energy, entropy, and Gibbs free energy in solids. Stability criteria. Bonding and electronic structure in metals, semiconductors, ionic crystals, and transition metal oxides. Point and line defects. Introduction to surfaces and amorphous materials. Instructors: Bernardi.

MS 132. Diffraction and Structure. 9 units (3–0–6); first term. *Prerequisites:* graduate standing or instructor's permission. Principles of electron, X-ray, and neutron diffraction with applications to materials characterization. Imaging with electrons, and diffraction contrast of crystal defects. Kinematical theory of diffraction: effects of strain, size, disorder, and temperature. Correlation functions in solids, with introduction to space-time correlation functions. Instructors: Fultz.

MS 133. Kinetic Processes in Materials. 9 units (3–0–6); third term. *Prerequisite:* APb 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. Instructor: Greer.

MS 142. Application of Diffraction Techniques in Materials Science. 9 units (2–3–4); second term. *Prerequisite:* MS 120 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. Instructor: Ahn.

MS/EST 143. Solid-State Electrochemistry for Energy Storage and Conversion. 9 units (3–0–6); third term. *Prerequisites:* MS 115 or MS 131, or instructor's permission. 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. Not offered 2015–16.

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. 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 2015–16.

MS/ME 166. Fracture of Brittle Solids. *9 units (3-0-6); third term.*
Prerequisites: MS 115a (or equivalent). The mechanical response of brittle materials (ceramics, glasses and some network polymers) will be treated using classical elasticity, energy criteria, and fracture mechanics. The influence of environment and microstructure on mechanical behavior will be explored. Transformation toughened systems, large-grain crack-bridging systems, nanostructured ceramics, porous ceramics, anomalous glasses, and the role of residual stresses will be highlighted. Strength, flaw statistics and reliability will be discussed. Instructors: Faber.

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

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: Hadian, Katz, Ramakrishnan, Graber, Ni, 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 2/102. Differential Equations. 9 units (4-0-5); first term. *Prerequisites: Ma 1 abc.* The course is aimed at providing an introduction to the theory of ordinary differential equations, with a particular emphasis on equations with well known applications ranging from physics to population dynamics. The material covered includes some existence and uniqueness results, first order linear equations and systems, exact equations, linear equations with constant coefficients, series solutions, regular singular equations, Laplace transform, and methods for the study of nonlinear equations (equilibria, stability, predator-prey equations, periodic solutions and limiting cycles). Instructors: Makarov, Zhou.

Ma 3/103. Introduction to Probability and Statistics. 9 units (4-0-5); second term. *Prerequisites: Ma 1 abc.* Randomness is not anarchy—it follows mathematical laws that we can understand and use to clarify our knowledge of the universe. This course is an introduction to the main ideas of probability and statistics. The first half is devoted to the fundamental concepts of probability theory, including distributions and random variables, independence and conditional probability, expectation, the Law of Averages (Laws of Large Numbers), and “the bell curve” (Central Limit Theorem). The second half is devoted to statistical reasoning: given our observations of the world, what can we infer about the stochastic mechanisms generating our data? Major themes include estimation of parameters (e.g. maximum likelihood), hypothesis testing, confidence intervals, and regression analysis (least squares). Students will be expected to be able to carry out computer-based analyses. Instructor: Border.

Ma 4/104. 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: Zhou.

Ma 5/105 abc. Introduction to Abstract Algebra. 9 units (3-0-6); *first, second, third terms.* 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. This course it to be taught concurrently with Ma 105. Instructors: Tsai, Mantovan, Ormerod.

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: Scheffer, Lupini.

Ma 7/107. 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 an $+ bn = cn$ and $a^2 - db^2 = A \pm 1$, constructible numbers, composition of binary quadratic forms, and congruences. Instructor: Ramakrishnan.

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: Mantovan.

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: Graber.

FS/Ma 12. The Mathematics of Enzyme Kinetics. 2-0-4; *third term.*

Prerequisites: Ma 1a, b. For course description, see Freshman Seminar. Not offered 2015-16.

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: Katz.

Ma 20. Frontiers in Mathematics. 1-0-0; *first term.* *Prerequisites:* Open for credit to freshman and sophomores. Weekly seminar by a member of the math department or a visitor, to discuss his or her research at an introductory level. The course aims to introduce students to research areas in mathematics and help them gain an understanding of the scope of the field. Graded pass/fail. Instructors: Katz.

Ma 92 abc. Senior Thesis. 9 units (0-0-9); *first, second, third terms.* *Prerequisites:* To register, the student must obtain permission of the mathematics undergraduate representative. 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 106. Elliptic Curves. 9 units (3-0-6); *third term.* *Prerequisites:* Ma 5 or equivalent. 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 2015–16.

Ma 108 abc. Classical Analysis. 9 units (3–0–6); first, second, third terms.

Prerequisites: Ma 1 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 \mathbb{R}^n . Second term: brief introduction to ordinary differential equations; Lebesgue integration and an introduction to Fourier analysis. Third term: the theory of functions of one complex variable. Instructors: Frank, Katz, Demerel.

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: Vafaei, Zhang, Markovic.

Ma 110 abc. Analysis. 9 units (3–0–6); first, second, third terms. *Prerequisites:*

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: Silva, Rains, Markovic.

Ma 111 ab. Topics in Analysis. 9 units (3–0–6); first, second, third terms. *Pre-*

requisites: 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. The third term will cover special functions: gamma functions, hypergeometric functions, beta/Selberg integrals and q -analogues. Time permitting: orthogonal polynomials, Painlevé transcendents and/or elliptic analogues. Instructors: Frank, Fathizadeh, Silva.

Ma 112 ab. Statistics. 9 units (3-0-6); second term. 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 2015-16.

Ma 116 abc. Mathematical Logic and Axiomatic Set Theory. 9 units (3-0-6); first, second, third terms. Prerequisites: Ma 5 or equivalent, or instructor's permission. First term: Introduction to first-order logic and model theory. The Gödel Completeness Theorem and the Completeness Theorem. Definability, elementary equivalence, complete theories, categoricity. The Skolem-Löwenheim Theorems. The back and forth method and Ehrenfeucht-Fraïssé games. Farkas theory. Elimination of quantifiers, applications to algebra and further related topics if time permits. Second and third terms: Axiomatic set theory, ordinals and cardinals, the Axiom of Choice and the Continuum Hypothesis. Models of set theory, independence and consistency results. Topics in descriptive set theory, combinatorial set theory and large cardinals. Instructor: Kechris.

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. Not offered 2015-16.

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 2015-16.

Ma 120 abc. Abstract Algebra. 9 units (3-0-6); first, second, third terms. Prerequisites: Ma 5 or equivalent or instructor's permission. This course will discuss advanced topics in algebra. Among them: an introduction to commutative algebra and homological algebra, infinite Galois theory, Kummer theory, Brauer groups, semisimple algebras, Wedderburn theorems, Jacobson

radicals, representation theory of finite groups. Instructors: Solis, Rains, Tsai.

Ma 121 ab. Combinatorial Analysis. 9 units (3-0-6); *first, second, 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: Omerod, Katz.

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 2015–2016.

Math 125. Algebraic Curves. 8 units (3-0-6). *Prerequisites: Ma 5.* An elementary introduction to the theory of algebraic curves. Topics to be covered will include affine and projective curves, smoothness and singularities, function fields, linear series, and the Riemann–Roch theorem. Possible additional topics would include Riemann surfaces, branched coverings and monodromy, arithmetic questions, introduction to moduli of curves. Not offered 2015–16.

EE/Ma/CS 126 ab. Information Theory. 9 units (3-0-6); *first, second terms. Prerequisites: Ma 2.* 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. Instructor: Solis, Graber, Ramakrishnan.

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. Not offered 2015–16.

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 2015–16.

Ma/ACM 142. Ordinary and Partial Differential Equations. 9 units (3-0-6); second 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: Frank.

Ma/ACM 144 ab. Probability. 9 units (3-0-6); first, second terms. Prerequisites: For 144a, Ma 108b is strongly recommended; for 144b, 108b and 144a are prerequisite. 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. Instructors: Makarov, Fathizadeh.

Ma 145 a. Representation Theory. 9 units (3-0-6); first term. Prerequisites: For 145a Ma 5 is a prerequisite; for 145b, Ma 108ab are strongly recommended. 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. Instructors: Rains

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. Not offered 2015–16.

Ma 148 ab. Topics in Mathematical Physics. 9 units (3-0-6); second, third terms. 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: Schrodinger 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. First term: geometric theory of quantum information and quantum entanglement based on information geometry and entropy. Instructor: Marcolli.

Ma 151 abc. Algebraic and Differential Topology. 9 units (3-0-6); first, second, third terms. Prerequisite: Ma 109 abc 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: Vafee, Ni.

Ma 157 ab. Riemannian Geometry. 9 units (3-0-6); second, third terms.

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: 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. Instructors: Trnkova, Zhang.

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, Mantovan.

Ma 162 ab. Topics in Number Theory. 9 units (3-0-6); second, third terms.

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. Not offered 2015-16.

Ma 191 abc. Selected Topics in Mathematics. 9 units (3-0-6); first, second, third terms.

Each term we expect to give between 0 and 6 (most often 2-3) topics courses in advanced mathematics covering an area of current research interest. These courses will be given as sections of 191. Students may register for this course multiple times even for multiple sections in a single term. The topics and instructors for each term and course descriptions will be listed on the math option website each term prior to the start of registration for that term. Instructor: Staff.

SS/Ma 214. Mathematical Finance. 9 units (3-0-6); first term. 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.

MECHANICAL ENGINEERING

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.

EE/ME 7. Introduction to Mechatronics. 6 units (2-3-1). For course description, see Electrical Engineering.

ME 8. Thinking Like an Engineer. 6 units (3-0-3); *second term*. An introduction to principles and techniques useful for Mechanical Engineering. Units and dimensional analysis; order-of-magnitude estimation; prototyping and model-scale experiments; visualization and computer-aided design. Case studies will be presented by weekly guest lecturers by practicing engineers in industry and academia. Not offered 2015–16.

ME 11 abc. Thermal Science. 9 units (3-0-6); *first, second, third terms*. *Prerequisites:* *Sophomore standing required; ME 12 abc, may be taken concurrently.* An introduction to classical thermodynamics and transport with engineering applications. First and second laws; closed and open systems; properties of a pure substance; availability and irreversibility; generalized thermodynamic relations; gas and vapor power cycles; propulsion; mixtures; combustion and thermochemistry; chemical equilibrium; momentum and heat transfer including boundary layers with applications to internal and external flows. Not offered on a pass/fail basis. Instructors: Hunt, Blaquart.

ME 12 abc. Mechanics. 9 units (3-0-6); *first, second, third terms*. *Prerequisites:* *Sophomore standing required; ME 11 abc, may be taken concurrently.* An introduction to statics and dynamics of rigid bodies, deformable bodies, and fluids. Equilibrium of force systems, principle of virtual work, distributed force systems, friction, static analysis of rigid and deformable structures, hydrostatics, kinematics, particle dynamics, rigid-body dynamics, Euler's equations, ideal flow, vorticity, viscous stresses in fluids, dynamics of deformable systems, waves in fluids and solids. Not offered on a pass/fail basis. Instructors: Mello, Andrade.

ME 13/130. Introduction to Mechanical Prototyping. 4 units (0-4-0); *first, second, 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 acquire the fundamental skills necessary to begin using 3D Computer Aided Design Software. Students will learn how to build parametric models of parts and assemblies and learn how to generate detailed drawings of their designs. Students will also be introduced to both manual and computer-aided machining techniques, as well as computer-controlled prototyping technologies, such as three-dimensional printing, laser cutting, 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. Instructors: Van Deusen.

ME 14. Design and Fabrication. 9 units (3-5-1); third term. Prerequisites: ME 12ab, ME 13. Enrollment is limited and will be based on responses to a questionnaire available in the Registrar's office. 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. Not offered on a pass/fail basis. Instructors: Mello, Van Deusen.

ME 50 ab. Experiments and Modeling in Mechanical Engineering. 9 units (0-6-3); second, third terms. Prerequisites: ME 11 abc, ME 12 abc, ME 13, ME 14, and programming skills at the level of CS 1 and ACM 11. Laboratory experiments and modeling of systems relevant to Mechanical Engineering. First offered 2015-2016. Instructors: Hall, Blanquart, Mello.

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. Not offered 2015-16.

ME 66. Vibration. 9 units (3-0-6); first 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 72 ab. Engineering Design Laboratory. 9 units (3-4-2) first term; (1-8-0) second term; first, second terms. Prerequisites: ME 14. Enrollment is limited. 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. Instructors: Mello, Van Duesen.

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: Blanquart.

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. Taught concurrently with ME 50 b. Not offered after 2015–2016.

ME 100. Independent Studies in Mechanical Engineering. *Units are assigned in accordance with work accomplished.* A faculty mentor will oversee a student proposed, independent research or study project to meet the needs of undergraduate students. Graded pass/fail. The consent of a faculty mentor and a written report is required for each term of work.

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/MedE 105 ab. Design for Freedom from Disability. *9 units (3–0–6); second, third terms.* For course description, see Engineering.

EST/EE/ME 109. Energy Technology and Policy. *9 units (3–0–6); first term.* 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.

CE/ME 112 ab. Hydraulic Engineering. *9 units (3–0–6).* For course description, see Civil Engineering.

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: Burdick.

MS/ME/MedE 116. Mechanical Behavior of Materials. 9 units (3-0-6); second term. For course description, see Materials Science.

ME 117. Nano-to-Macro Transport Processes. 9 units (3-0-6); second term. Prerequisites: ME 11 abc, ME 12 abc, ACM 95 or equivalent. This course provides a parallel treatment of photons, electrons, phonons, and molecules as energy carriers, aiming at fundamental understanding and descriptive tools for energy and heat transport processes from the nanoscale continuously to the macroscale. Topics include energy transport in the form of waves and particles, scattering and heat generation processes, Boltzmann equation and derivation of classical laws, deviation from classical laws at the nanoscale and their appropriate descriptions, with applications in nano- and microtechnology. Not offered 2015–16.

Ae/ME 118. Classical Thermodynamics. 9 units (3-0-6); first term. For course description, see Aerospace.

ME 119 ab. Heat and Mass Transfer. 9 units (3-0-6); first, second terms. Prerequisites: ME 11 abc, ME 12 abc, 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: Minnich

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 2015–16.

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. Not offered 2015–16.

AM/CE/ME 150 abc. Graduate Engineering Seminar. 1 unit; each term. For course description, see Applied Mechanics.

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.

ME/CE 163. Mechanics and Rheology of Fluid-Infiltrated Porous Media. 9 units (3-0-6); second term. *Prerequisites:* Continuum Mechanics - Ae/Ge/ME 160 ab. This course will focus on the physics of porous materials (e.g., geomaterials, biological tissue) and their intimate interaction with interstitial fluids (e.g., water, oil, blood). The course will be split into two parts: Part 1 will focus on the continuum mechanics (balance laws) of multi-phase solids, with particular attention to fluid diffusion-solid deformation coupling. Part 2 will introduce the concept of effective stresses and state of the art rheology available in modeling the constitutive response of representative porous materials. Emphasis will be placed on poro-elasticity and poro-plasticity. Instructor: Andrade.

AM/ME 165 ab. Elasticity. 9 units (3-0-6). For course description, see Applied Mechanics.

MS/ME 166. Fracture of Brittle Solids. 9 units (3-0-6); third term. For course description, see Materials Science.

CE/ME/Ge 173. Mechanics of Soils. 9 units (3-0-6); second term. For course description, see Civil Engineering.

ME/CE/Ge 174. Mechanics of Rocks. 9 units (3-0-6); third term. *Prerequisites:* Ae/Ge/ME 160a. Basic principles of deformation, strength, and stressing of rocks. Elastic behavior, plasticity, viscoelasticity, viscoplasticity, creep, damage, friction, failure mechanisms, shear localization, and interaction of deformation processes with fluids. Engineering and geological applications. Instructors: Lapusta.

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. A faculty mentor will oversee a student proposed, independent research or study project to meet the needs of graduate students. Graded pass/fail. The consent of a faculty mentor and a written report is required for each term of work.

ME 201. Advanced Topics in Mechanical Engineering. 9 units (3-0-6). The faculty will prepare courses on advanced topics to meet the needs of graduate students.

ME 202 abc. Engineering Two-Phase Flows. 9 units (3-0-6). *Prerequisites:* ACM 95/100 ab, 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 2015–16.

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/ME 218. Statistical Mechanics. 3-0-6; second term. For course description, see Aerospace.

CE/Ge/ME 222. Earthquake Source Processes, Debris Flows, and Soil Liquefaction: Physics-based Modeling of Failure in Granular Media. 6 units (2-0-4); third term. For course description, see Civil Engineering.

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.

Ae/CDS/ME 251 ab. Closed Loop Flow Control. 9 units; (3-0-6 a, 1-3-5- b). For course description, see Aerospace.

ME/MS 260 ab. Micromechanics. 12 units (3-0-9); second, third terms. *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 2015–16.

ME/Ge/Ae 266 ab. Dynamic Fracture and Frictional Faulting. 9 units (3-0-6); second, third terms. Prerequisites: 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. Not offered 2015-16.

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.

MEDICAL ENGINEERING

MedE 99. Undergraduate Research in Medical Engineering. 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 co-advised by a Caltech faculty member and an external researcher. Graded pass/fail. Instructor: Staff.

MedE 100 abc. Medical Engineering Seminar. 1 unit; first, second, third terms. All PhD degree candidates in Medical Engineering are required to attend all MedE seminars. If there is no MedE seminar during a week, then the students should go to any other graduate-level seminar that week. Students should broaden their knowledge of the engineering principles and sciences of medical engineering. Students are expected to learn the forefronts of the research and development of medical materials, technologies, devices and systems from the seminars. Graded pass/fail. Instructor: Choo.

MedE 101. Introduction to Clinical Physiology and Pathophysiology for Engineers. 9 units, 3-0-6; First term. Prerequisites: No Prerequisites, Bi 1 or equivalent recommended. The goal of this course is to introduce engineering scientists to medical physiological systems: with a special emphasis on the clinical relevance. The design of the course is to present two related lectures each week in a case study format: An overview of the physiology of a system followed by examples of pathophysiology as well as diagnostic and therapeutic modalities. The Final two weeks of the course will be a mini-work shop where the class explores challenging problems in medical physiology. The course ultimately seeks to promote a bridge between relevant clinical problems and engineering scientists who desire to solve them. Graded pass/fail. Instructor: Petrasek.

E/ME/MedE 105 ab. Design for Freedom from Disability. 9 units (3-0-6). For course description, see Engineering.

BE/Bi/MedE 106. Introduction to Biomechanics. 9 units (3-0-6). For course description, see Bioengineering.

ChE/BE/MedE 112. Design, Invention, and Fundamentals of Microfluidic Systems. 9 units (3-0-6). For course description, see Chemical Engineering.

EE/MedE 114ab. Analog Circuits Design. 12 units (4-0-8); second and third term. For course description, see Electrical Engineering.

EE/MedE 115. Micro-/Nano-scales Electro-optics. 9 units (3-0-6); first term. For course description, see Electrical Engineering.

MS/ME/MedE 116. Mechanical Behavior of Materials. 9 units (3-0-6). For course description, see Materials Science.

EE/MedE 124. Mixed-mode Integrated Circuits. 9 units (3-0-6); third term. For course description, see Electrical Engineering.

EE/BE/MedE 166. Optical Methods for Biomedical Imaging and Diagnostics. 9 units (3-1-5); third term. For course description, see Electrical Engineering.

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

EE/MedE 187. VLSI and ULSI Technology. 9 units (3-0-6); third term. For course description, see Electrical Engineering.

ChE/BE/MedE 188. Molecular Imaging. 9 units (3-0-6). For course description see Chemical Engineering.

BE/EE/MedE 189 ab. Design and Construction of Biodevices. 12 units (3-6-3) a; 9 units (0-9-0) b. For course description, see Bioengineering.

MedE 199. Special Topics in Medical Engineering. *Units to be arranged, terms to be arranged.* Subject matter will change from term to term depending upon staff and student interest, but will generally center on the understanding and applying engineering for medical problems. Instructor: Staff.

MedE 201ab. Principles and Design of Medical Devices. 9 units (3-0-6); second and third term. *Prerequisite: instructor's permission.* This course provides a broad coverage on the frontiers of medical diagnostic and therapeutic technologies and devices based on multidisciplinary engineering principles. Topics include biomaterials and biomechanics; micro/nanofluidics; micro/nano biophotonics and medical imaging; medical electronics, wireless communications through the skin and tissue; electrograms and biotic/abiotic interface; biochips, microPCR and sequencer and biosensors; micro/nano implants. The course will focus on the scientific fundamentals specific to medical applications. However, both the lectures and assignments will also

emphasize the design aspects of the topics as well as up-to-date literature study. Instructors: Tai, Choo.

MedE 205. New Frontiers in Medical Technologies. 6 units, (2-0-4); third term. Prerequisites: None but knowledge of semiconductor physics and some system engineering, basic electrical engineering highly recommended. New Frontiers of Medical Technologies is an introductory graduate level course that describes space technologies, instruments, and engineering techniques with current and potential applications in medicine. The main thrust of these medical engineering elements development has been toward space exploration. Spinoff applications to medicine has been explored and proven with various degrees of success and maturity. This class introduces these topics, their intended original space applications and the medical applications. Topics include but not limited to multimodal imaging, UV/Visible/NIR imaging, imaging spectrometry, sensors, robotics, and navigation. Instructor: Shouleh Nikzad.

MedE/BE/Ae 243. Biological Flows: Transport and Circulatory Systems. 9 units (3-0-6); second 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. Instructor: Pahlevan.

MedE 291. Research in Medical Engineering. Units to be arranged, first, second, third terms. Qualified graduate students are advised in medical engineering research, with the arrangement of MedE staff.

MUSIC

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 2015–16.

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. Not offered 2015–16.

Mu 26. Jazz History. *9 units (3-0-6); third 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. Not offered 2015–16.

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. Instructor: Neenan.

Mu 29. Harmony II. *9 units (3-0-6), third term. Prerequisite: Mu 28 or entrance exam.* More advanced concepts of music theory, including chromatic harmony, and 20th-century procedures relating to selected popular music styles; ear training, continued. Instructor: Neenan.

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 2015–16.

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. Not offered 2015–16.

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. Not offered 2015–16.

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.

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.

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. Not offered 2015–16.

NEUROBIOLOGY

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

Bi/CNS/NB 153. Brain Circuits. 9 units (3-0-6); *second term.* For course description, see Biology.

Bi/NB/BE 155. Neuropharmacology. 6 units (3-0-3); *second term.* For course description, see Biology.

Bi/NB 156. Molecular Basis of Behavior. 9 units (3-0-6); *second term.* For course description, see Biology.

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

Bi/CNS/NB 162. Cellular and Systems Neuroscience Laboratory. 12 units (2-7-3); *third term.* Prerequisites: Bi/CNS/NB 150 or instructor's permission. For course description, see Biology.

Bi/CNS/NB 164. Tools of Neurobiology. 9 units (3-0-6); *second term.* Prerequisites: Bi/CNS/NB 150 or equivalent. For course description, see Biology.

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

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

Bi/CNS/NB 185. Large Scale Brain Networks. 6 (2-0-4); third term. For course description, see Biology.

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

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

Bi/CNS/NB 195. Mathematics in Biology. 9 units (3-0-6); second term. For course description, see Biology.

BE/Bi/NB 203. Introduction to Programming for the Biological Sciences Bootcamp. 6 units; summer. For course description, see Bioengineering.

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

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

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

Bi/CNS/BE/NB 230. Optogenetic and CLARITY Methods in Experimental Neuroscience. 9 units (3-2-4); third term. For course description, see Biology.

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

Bi/CNS/NB 250c. Topics in Systems Neuroscience. 9 units (3-0-6); third term. For course description, see Biology.

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

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 15abc. Student Publications. *3 units (1-0-2); first, second, third terms.* The elementary principles of newspaper writing and editing, with special attention to producing articles for the student publication. Instructor: Kipling.

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: 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: Sulhian.

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>.

PHILOSOPHY

Hum/PI 8. Right and Wrong. *9 units (3-0-6).* For course description, see Humanities.

Hum/PI 9. Knowledge and Reality. *9 units (3-0-6).* For course description, see Humanities.

PI 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.

PI 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.

PI/Law 99. Causation and Responsibility. 9 units (3–0–6); *first term.* This course will examine the interrelationships between the concepts of causation, moral responsibility, and legal liability. It will consider legal doctrines of causation and responsibility, as well as attempts within philosophy to articulate these concepts. Questions to be addressed include: Can you be morally or legally responsible for harms that you do not cause? Is it worse to cause some harm, than to unsuccessfully attempt it? Is it justified to punish those who cause harm more severely than those who attempt harm? When, if ever, can the ends justify the means? What constitutes negligence? Is it worse to cause some harm, than to allow it to happen (when you could have prevented it)? Not offered 2015–16.

PI 100. Free Will. 9 units (3–0–6); *first term.* This course examines the question of what it means to have free will, whether and why free will is desirable, and whether humans have free will. Topics may include historical discussions of free will from writers such as Aristotle, Boethius, and Hume; what it means for a scientific theory to be deterministic, and whether determinism is compatible with free will; the connection between free will and moral responsibility; the relationship between free will and the notion of the self; beliefs about free will; the psychology of decision making; and the insanity defense in law. Instructors: Hitchcock.

PI 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.*

PI 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 2015–16.

HPS/PI 120. Introduction to Philosophy of Science. 9 units (3–0–6). For course description, see History and Philosophy of Science.

HPS/PI 121. Causation and Explanation. 9 units (3–0–6). For course description, see History and Philosophy of Science.

HPS/PI 122. Probability, Evidence, and Belief. 9 units (3–0–6). For course description, see History and Philosophy of Science.

HPS/PI 123. Introduction to the Philosophy of Physics. 9 units (3-0-6); *first term*. For course description, see History and Philosophy of Science.

HPS/PI 124. Philosophy of Space and Time. 9 units (3-0-6). For course description, see History and Philosophy of Science.

HPS/PI 125. Philosophical Issues in Quantum Physics. 9 units (3-0-6); *third term*. For course description, see History and Philosophy of Science.

HPS/PI 128. Philosophy of Mathematics. 9 units (3-0-6). For course description, see History and Philosophy of Science.

HPS/PI 129. Introduction to Philosophy of Biology. 9 units (3-0-6). For course description, see History and Philosophy of Science.

HPS/PI 130. Philosophy and Biology. 9 units (3-0-6). For course description, see History and Philosophy of Science.

HPS/PI 132. Introduction to Philosophy of Mind and Psychology. 9 units (3-0-6). For course description, see History and Philosophy of Science.

HPS/PI 134. Current Issues in Philosophical Psychology. 9 units (3-0-6). For course description, see History and Philosophy of Science.

HPS/PI 135. Moral Philosophy and the Brain. 9 units (3-0-6); *second term*. For course description, see History and Philosophy of Science.

HPS/PI 136. Happiness and the Good Life. 9 units (3-0-6); *third term*. For course description, see History and Philosophy of Science.

HPS/PI 138. Human Nature and Society. 9 units (3-0-6). For course description, see History and Philosophy of Science.

PI 150. 17th-Century Philosophy: Bacon to Leibniz. 9 units (3-0-6); *second terms*. The course will examine the work of one or more 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. Not offered 2015–16.

PI 151. 18th-Century Philosophy: Locke to Kant. 9 units (3-0-6); *first term*. The course will examine the work of one or more 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. Not offered 2015–16.

HPS/PI 165. Selected Topics in Philosophy of Science. 9 units (3–0–6); For course description, see History and Philosophy of Science.

HPS/H/PI 173. History of Chemistry. 9 units (3–0–6); *second term.* For course description, see History and Philosophy of Science.

HPS/H/PI 176. History of Alchemy. 9 units (3–0–6); *third term.* For course description, see History and Philosophy of Science.

PI/HPS 183. Bioethics. 9 units (3–0–6); *offered by announcement.* A survey of issues in bioethics. Topics may include: abortion and reproductive rights; euthanasia; cloning; genetic modification of organisms (including humans); moral status of chimeras; stem-cell research; organ transplantation, distribution and sale; cure vs. enhancement; use of human subjects in research; the concept of informed consent; research on non-human animals. Instructors: Cowie, Manning.

PI 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 2015–16.

PI 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 2015–16.

HPS/PI 188. The Evolution of Cognition. 9 units (3–0–6). For course description, see History and Philosophy of Science.

PHYSICAL EDUCATION

PE 1. Student Designed Fitness. *3 units; first, second, third terms; May only be used for 3 units of the 9-unit physical education requirement.* This course provides students with knowledge and practical opportunities to develop and implement an individualized program to successfully accomplish their physical fitness goals. Detailed proposals are developed during week two of the term, and journals are maintained throughout the term to monitor progress. Instructors: Staff

PE 2. Healthier Living. *3 units; second term. May only be used for 3 units of the 9-unit physical education requirement.* This course is designed to educate students and increase awareness of the dimensions of health and wellness. The course will be implemented through personal assessment, active participation, guest lectures, and engaging dialogue. In addition, the course will emphasize positive personal healthful decisions and encourage students to adopt behaviors to minimize health risks, enhance overall wellness, and foster healthy active lifestyles across the lifespan. Instructor: Staff

PE 3. Hiking. *3 units; first, second, third terms.* This course is designed to provide students an opportunity to explore the outdoors of Pasadena and the San Gabriel Mountains while participating in physical fitness activities. Learn about proper hiking gear, basics for safety, trip plans, and how to research trails in the local area. The class will meet on campus and then travel to one of the local trails for an afternoon hike. Students will be asked to use maps, compass, and GPS devices on various hikes to teach them proper use of all forms of location guidance. Along the trail, students will be asked to identify local flora and vegetation, learn trail etiquette, discuss survival scenarios in the event of emergency, and practice basic trail first aid. Topics such as trail nutrition and hydration will be presented, and students will create a search and rescue plans in the event of an overnight emergency. *This class will only be offered on Friday afternoon in the fall and spring, meeting once per week for a three hour block to accommodate travel off campus.* Instructor: Staff.

PE 4. Introduction to Power Walking. *3 units; third term.* 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: Staff.

PE 5. Beginning Running - Half Marathon Training. *3 units; third term.* This course helps anyone learn to conquer the distance of a half marathon, regardless of your previous running experience. Beginners welcome! Learn to complete a distance event using the Jeff Galloway method of training., which employs run/walk cycles to provide runners with rest and recovery while tackling the long mileage of a half marathon. This course will give students a training schedule, determine the individually appropriate run walk ratio, and help students find an appropriate pace that fits their running ability. Class sessions include a short lecture and run, with students designing a long run course for themselves and running longer mileage on a third day outside of class meetings. Short topics such as hydration, nutrition, race strategy, proper clothing, and shoe choices will be given at the beginning

of each session. Speed work options are provided for runners who want to increase their pace. Students are encouraged but not required to pick a race to participate in toward the end of the term. Instructor: Staff.

PE 6. Core Training, Beginning/Intermediate. *3 units; first, second, third terms.* Learn to develop functional fitness using core stability training techniques that focus on working 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. Speed and Agility Training, Beginning/Intermediate. *3 units; second term.* 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 development of an individual or sport-specific training workout will be taught. Instructor: Staff.

PE 8. Fitness Training, Beginning. *3 units; first, second, third terms.* An introductory course 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 be able to design an exercise program for lifelong fitness. Instructor: Staff.

PE 9. Soccer. *3 units; third term.* Fundamental instruction on shooting, passing, trapping, dribbling, penalty kicks, offensive plays, defensive strategies, and goal keeping. Course includes competitive play using small field and full field scrimmages. Instructor: Staff.

PE 10. Aerobic Dance. *3 units; first, second, third terms.* Each class includes a thorough warm-up, a cardiovascular workout phase that 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 14. Basketball Skills, Beginning and Beginning/Intermediate. *3 units; third term.* Features fundamental instruction on shooting, dribbling, passing, defensive positioning, and running an offense. Course includes competitive play and free-throw shooting. Instructors: Staff.

PE 20. Fencing, Beginning and Intermediate/Advanced. *3 units; first term.* 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 24. Yoga, Beginning. *3 units; first, second, third terms.* 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 activ-

ity designed to reduce stress for improved health of body and mind while increasing flexibility, strength, and stamina, and reducing chance of athletic injury. Instructor: Staff.

PE 27. Ultimate Frisbee. *3 units; third term.* 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 skills necessary to play the game confidently on a recreational basis. Instructor: Staff.

PE 28. Flying Saucers. *3 units; first, second terms.* This course is designed to provide students an opportunity to learn proper techniques, form, rules, and game play for various Frisbee activities including Frisbee golf, Frisbee tag, and Ultimate Frisbee while promoting healthy lifestyle behaviors. Students will also improve hand-eye coordination, agility, and foot speed. Instructors: Staff.

PE 30. Golf, Beginning, Intermediate, and Advanced. *3 units; second, third terms.* Beginning course 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 course 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 31. Indoor/Outdoor Cycling. *3 units; first term.* During this introductory course surveying a variety of cycling disciplines including mountain biking, road biking, cyclocross, velodrome, and indoor cycling, students will learn proper cycling techniques, bike handling, set-up, safety, and maintenance. Students will also learn and apply principles of lifetime physical fitness utilizing major components of cardio-respiratory endurance, muscular strength and endurance, and flexibility. It is recommended students have a bicycle however a limited number of bikes will be provided as needed. Students will be required to have and wear a helmet for all class cycling activities. Instructors: Staff.

PE 33. Beginning Triathlon Training. *3 units; first term.* This course is designed to help beginners learn to train for a sprint distance triathlon. All three disciplines will be taught, with specific technique instruction in each area. Students will learn how to develop a training schedule, choosing the correct event for their skill, nutrition, safety, and race preparation. The course will include techniques to increase transition efficiency, trouble shoot issues on the route and strategies to record a personal best in future races. Safe training to reduce injury and assure a healthy race is the foundation of this course. Instructor: Staff.

PE 35. Diving, Beginning/Intermediate. *3 units; first term.* Students will learn fundamentals of springboard diving to include basic approach, and five standard dives. Intermediate course includes instruction in the back

somersault, forward somersault, forward somersault full twist, and reverse somersault. Instructor: Staff.

PE 36. Swimming, Beginning/Intermediate and Advanced. *3 units; first, second, third terms.* Instruction in all basic swimming strokes, including freestyle, elementary backstroke, racing backstroke, breaststroke, sidestroke, and butterfly. Advanced course focuses on proper technique of the four competitive strokes using video and drills along with instruction on training methods and proper workout patterns. Instructor: Staff.

PE 37. Beginning Kayaking. *3 units; first term.* This course will provide instruction in basic kayaking skills including kayaking outfitting, stroke technique, self-rescue and kayak maneuvering. The goal is for students to learn to navigate turbulent ocean waters or through whitewater rapids on rivers. No kayaking experience is required. Instruction will focus on whitewater application to ocean kayaking. Students will learn basic paddle techniques and craft control, and a self rescue technique progression culminating in the C-to-C kayak roll. Trips to local bays and rivers will be included and are optional. Class meetings will be held in the Caltech pool. Course Requirement - Students must be a proficient swimmer or be able to successfully complete an in water swim test. Instructors: Staff.

PE 38. Water Polo. *3 units; second term.* Basic recreational water polo with instruction of individual skills and team strategies. A background in swimming is encouraged. Instructor: Staff.

PE 40. Beginning Self Defense. *3 units.* Students will learn basics of keeping themselves safe when an unknown person threatens their safety. The course is focused on staying safe while rendering an assailant temporarily unable to give chase to allow the student to get help. Techniques taught will assist students in learning vulnerable targets to disable an attacker, using their own body to maximize damage to allow escape, and finding methods to generate force. Using an assailant's attack against him to maintain balance and administer the greatest degree of force necessary to disable a threat is the foundation of the course.

PE 44. Karate (Shotokan), Beginning and Intermediate/Advanced. *3 units; first and third terms.* 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. 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.

PE 48. T'ai-Chi Ch'uan, Beginning and Intermediate/Advanced. *3 units; second term.* Chinese movement art emphasizing relaxation and calm awareness through slow, flowing, meditative movement using only minimum strength needed to accomplish the action. Instructor: Staff.

PE 50. Badminton, Beginning/Intermediate. *3 units; third term.* 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, serve returns, forehand and backhand smash returns, attacking clears, and sliced drop shots are taught. Singles and doubles play along with drill work throughout the term. Instructor: Staff.

PE 54. Racquetball, Beginning and Intermediate/Advanced. *3 units; first, second, third term.* 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, serves, and daily games. Instructor: Staff.

PE 56. Squash, Beginning, Intermediate, Advanced. *3 units; second term.* Learn by playing as 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 course will concentrate on skill development with inclusion of forehand and backhand drives, lobs, volleys, and drops, with emphasis on court movement, shot selection, and tactics. Instructor: Staff.

PE 60. Tennis, Beginning, Intermediate, and Advanced. *3 units; first, second, third terms.* Stroke fundamentals, singles and doubles play, plus rules, terminology, and etiquette are covered in all classes. Beginning course emphasizes groundstrokes, volleys, serve, and grips. Beginning/Intermediate course is for those players 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. Instructor: Staff.

PE 70. Weight Training, Beginning/Intermediate. *3 units; first, second, third terms.* 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 isokinetic strength and cardiovascular fitness training. Instructor: Staff.

PE 71. Advanced Techniques of Human Performance. *3 units; first, third terms.* Prerequisites: PE 70, instructor approval. This course is intended for those experienced with high level physical training. This course helps individuals improve sport and physical fitness skills by addressing components including muscular strength, foot speed, agility, cardiovascular conditioning and flexibility. Instructor: Staff.

PE 77. Volleyball, Beginning, Intermediate, and Advanced. *3 units; third term.* Fundamental instruction on drills, strategies, and rules, with game-playing opportunities. 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 courses 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. Does not satisfy the Institute physical education requirement.* 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. Instructor: Staff.

PE 81. Bouldering. *3 units; first, second term. Taught at the Caltech bouldering cave, Brown Gym.* During this introductory course to bouldering, students will learn terminology, how to properly fit into a harness, set-up and use a tubular belay device, and belay commands. This course will emphasize muscle strength and endurance, balance, and flexibility, as well as be challenging for mind and body. Instructors: Staff.

PE 82. Rock Climbing, Beginning/Intermediate. *3 units; first, second, third terms. Taught at the Caltech Climbing Wall, Brown Gym.* 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. Instructor: Staff.

PE 84. Table Tennis, Beginning/Intermediate. *3 units; second term.* 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 ab. Intercollegiate Basketball Team (Women). *3 units; first, second terms.* Coach: Marbut.

PE 85 ab. Intercollegiate Track and Field Team (Men and Women). *3 units; second, third terms.* Coach: Raphelson.

PE 87 ab. Intercollegiate Swimming Team (Men and Women). *3 units; first, second terms.* Coach: Leavitt.

PE 89 ab. Intercollegiate Fencing Team (Men and Women).

3 units; first, second terms. Coach: Corbit.

PE 90 abc. Intercollegiate Water Polo Team (Men and Women).

3 units; first term Men; second, third term Women. Coach: Staff.

PE 91 ab. Intercollegiate Basketball Team (Men).

3 units; first, second terms. Coach: Eslinger.

PE 92. Intercollegiate Soccer Team (Men).

3 units; first term. Coach: Murray

PE 93 ab. Intercollegiate Baseball Team (Men).

3 units; second, third terms. Coach: Mark.

PE 95 ab. Intercollegiate Tennis Team (Men).

3 units; second, third terms. Coach: Gamble.

PE 96 ab. Intercollegiate Tennis Team (Women).

3 units; second, third terms. Coach: Gamble.

PE 97. Intercollegiate Cross-Country Team (Men and Women).

3 units; first term. Coach: Raphelson.

PE 99. Intercollegiate Volleyball Team (Women).

3 units; first term. Coach: Gardner.

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: Patterson, Hsieh, Martin, Alicea.

Ph 2 abc. Waves, Quantum Mechanics, and Statistical Physics.

9 units (3-0-6); first, second, third terms. Prerequisites: Ph 1 abc, Ma 1 abc. An introduction to several areas of physics including applications in modern science and engineering. Topics include discrete and continuous oscillatory systems, wave mechanics, applications in telecommunications and other areas (first term); foundational quantum concepts, the quantum harmonic oscillator, the Hydrogen atom, applications in optical and semiconductor systems (second term); ensembles and statistical systems, thermodynamic laws, applications in energy technology and other areas (third term). Although best

taken in sequence, the three terms can be taken independently. Instructor: Martin, Politzer, Cheung, Filippone.

Ph 3. Physics Laboratory. 6 units (0-3-3); first, second, third terms. *Prerequisite:* Ph 1 a or instructor's permission. An introduction to experimental techniques and instruments used in the physical sciences, covering topics in classical mechanics, basic electronic circuits, and optics. Special emphasis is given to data analysis techniques based on modern statistical methods. The weekly structure of the course includes one three-hour laboratory session, a conference with the instructor, a set of pre-lab problems, and analysis of experimental results. Graded pass/fail unless a letter grade is requested. Only one term may be taken for credit. Instructors: Black, Libbrecht.

FS/Ph 4. Freshman Seminar: Astrophysics and Cosmology with Open Data. 6 units (3-0-3); first term. For course description, see Freshman Seminar.

Ph 5. Analog Electronics for Physicists. 9 units (0-5-4); first term. *Prerequisites:* Ph 1 abc, Ph 3, or equivalents (Ph 8 may be substituted for Ph 3). A laboratory course focusing on practical electronic circuits, with emphasis on analog electronics. The following topics are studied: RC circuits, electrical oscillations, operational amplifiers, diodes and transistors, combining circuit elements, and computer data acquisition. The course culminates in a two-week project of the student's choosing. Instructors: Rice, 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, Politzer.

Ph 7. Physics Laboratory. 9 units; third term. *Prerequisites:* Ph 6. 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, Politzer.

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: Spiropulu.

FS/Ph 9. Freshman Seminar: The Science of Music. 6 units (2-0-4). For course description, see Freshman Seminar.

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: Soifer.

FS/Ph 11 abc. Research Tutorial. 6 units (2-0-4). For course description, see Freshman Seminar.

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: Chen, Filippone, Preskill.

FS/Ph 15. Freshman Seminar: Dance of the Photons. 6 units (2-0-4); second term. For course description, see Freshman Seminar.

Ph 20. Computational Physics Laboratory I. 6 units (0-6-0); first, second, third terms. Prerequisites: CS 1 or equivalent. Introduction to the tools of scientific computing. Use of numerical algorithms and symbolic manipulation packages for solution of physical problems. Python for scientific programming, Mathematica for symbolic manipulation, Unix tools for software development. Instructors: Mach, Weinstein.

Ph 21. Computational Physics Laboratory II. 6 units (0-6-0); second, third terms. Prerequisites: Ph 20 or equivalent experience with programming. Computational tools for data analysis. Use of python for accessing scientific data from the web. Bayesian techniques. Fourier techniques. Image manipulation with python. Instructors: Mach, Weinstein.

Ph 22. Computational Physics Laboratory III. 6 units (0-6-0); third term. Prerequisites: Ph 20 or equivalent experience with programming and numerical techniques. Computational tools and numerical techniques. Applications to problems in classical mechanics. Numerical solution of 3-body and N-body systems. Monte Carlo integration. Instructors: Mach, Prince.

Ph 50 abc. Caltech Physics League. 4 units (1-0-3); first, second 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); first, 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); third term. Emphasis will be on using basic physics to understand complicated systems. Examples will be selected from properties of materials, geophysics, weather, planetary science, astrophysics, cosmology, biomechanics, etc. Not offered 2015-16.

Ph 103. Atomic and Molecular Spectroscopy. 9 units (3-0-6); second term. Prerequisites: instructor's permission. 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. Not offered 2015-16.

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 (Ph 8 may be substituted for Ph 3). A laboratory course focusing on practical electronic circuits, with emphasis on analog electronics. The following topics are studied: RC circuits, electrical oscillations, operational amplifiers, diodes and transistors, combining circuit elements, and computer data acquisition. The course culminates in a two-week project of the student's choosing. Instructors: Rice, 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: Golwala, Chen.

APh/Ph 115. Physics of Momentum Transport in Hydrodynamic Systems. 12 units (3-0-9). For course description, see Applied Physics.

APh/Ph/Ae 116. Physics of Thermal and Mass Transport in Hydrodynamic Systems. 12 units (3-0-9). For course description, see Applied Physics.

Ph/APh/EE/BE 118 ab. Physics of Measurement. 9 units (3-0-6); first and second terms. Prerequisites: Ph127, APb 105, or equivalent, or permission from instructor. This course focuses on exploring the fundamental underpinnings of experimental measurements from the perspectives of responsivity, noise, backaction, and information. Its overarching goal is to enable students to critically evaluate real measurement systems, and to determine the ultimate fundamental and practical limits to information that can be extracted from them. Topics will include physical signal transduction and responsivity, fundamental noise processes, modulation, frequency conversion, synchronous detection, signal-sampling techniques, digitization, signal transforms, spectral analyses, and correlations. The first term will cover the essential fundamental underpinnings, while topics in second term will include examples from optical methods, high-frequency and fast temporal measurements, biological interfaces, signal transduction, biosensing, and measurements at the quantum limit. Instructor: Roukes.

Ph/APh/EE/BE 118 c. Physics of Measurement. 9 units (3-0-6); *third terms. Prerequisites: Ph127, APh 105, or equivalent, or permission from instructor.* Ph118c will focus on the physical principles and applications of several important measurement techniques to modern condensed matter physics research. The course will begin with an introduction of the concept of self-energy and Green function techniques in the descriptions of many-body interactions. Several representative experimental techniques for investigating important physical properties of many-body systems will be discussed, followed by explicit examples for their applications to condensed matter physics research. The measurement techniques will include scanning probe microscopy, angle-resolved photoemission spectroscopy, optical measurements, and thermodynamic and electrical transport measurements. Instructor: Yeh.

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. Instructors: Wise, Cheung.

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: Alicea, Motrunich, Refael.

Ph 129 abc. Mathematical Methods of Physics. 9 units (3-0-6); *first, second, third terms. Prerequisites: Ph 106 abc and ACM 95/100 ab 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 covers probability and statistics in physics. Third term focuses on group theoretic methods in physics. The three terms can be taken independently. Instructors: Porter, Chen.

Ph 135 abc. Applications of Quantum Mechanics. 9 units (3-0-6); *first, second, third terms. Prerequisites: Ph 125 abc or equivalent.* Applications of quantum mechanics to topics in contemporary physics. First term: introduction to condensed matter which covers electronic properties of solids, including band structures, transport, and optical properties. Ph 135a is continued by Ph 223 ab in second and third terms. Second term: introduction to particle physics which includes Standard Model, Feynman diagrams, matrix elements, electroweak theory, QCD, gauge theories, the Higgs mechanism, neutrino mixing, astro-particle physics/cosmology, accelerators, experimental techniques, important historical and recent results, physics beyond the Standard Model, and major open questions in the field. Third

term: an overview of modern Quantum Optics with particular emphasis on quantum measurement science, the quantum-classical interface, quantum networks, and quantum many-body physics with atoms and photons. The course will concentrate on the essential roles of manifestly quantum (i.e., nonclassical) and entangled states of light and matter. The course covers theoretical tools for analyses of coherent light-matter interactions including the quantum master equation, and will combine examples on both theory and experiment from the current research literature. This is a one-term class aimed at advanced undergraduates as well as beginning graduate students. Terms may be taken independently. Instructors: Motrunich, Patterson, Kimble.

Ph 136 abc. Applications of Classical Physics. *9 units (3-0-6); first, second, third terms. Prerequisites: 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. Ph 136a will focus on thermodynamics, statistical mechanics, random processes, and optics. Ph136b will focus on fluid dynamics, MHD, turbulence, and plasma physics. Ph 136c will cover an introduction to general relativity. Instructors: Ott, Scheel.

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. The instructor will complete a student evaluation at the end of the term. Graded pass/fail.

Ph 172. Research in Experimental Physics. *Units in accordance with work accomplished.* Students registering for 6 or more units of Ph 172 must give a 15-minute oral presentation to the Physics Undergraduate Committee at the Physics Undergraduate Research Seminar Day. Approval of the student’s research supervisor and departmental adviser must be obtained before registering. Graded pass/fail.

Ph 173. Research in Theoretical Physics. *Units in accordance with work accomplished.* Students registered for 6 or more units of Ph 173 must give a 15-minute oral presentation to the Physics Undergraduate Committee at the Physics Undergraduate Research Seminar Day. Approval of the student’s research supervisor and departmental adviser must be obtained before registering. Graded pass/fail.

CNS/Bi/Ph/CS/NB 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 the physics at the Large Hadron Collider. Topics include the Standard Model of particle physics in light of the discovery of the Higgs boson, work towards the characterization and measurements of the new particle's quantum properties, its implications on physics beyond the standard model, and its connection with the standard model of cosmology focusing on the dark matter challenge. 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. Not offered 2015–2016.

Ph 205 abc. Relativistic Quantum Field Theory. 9 units (3–0–6); *first, second, third terms. Prerequisites: 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: Gukov, Wise.

Ph 217. Introduction to the Standard Model. 9 units (3–0–6); *first term. Prerequisites: Ph 205 abc and Ph 236 abc, or equivalent.* An introduction to 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. Instructors: Cheung.

Ph/CS 219 abc. Quantum Computation. 9 units (3–0–6); *first, second, third terms. Prerequisite: Ph 129 abc or equivalent.* The theory of quantum information and quantum computation. Overview of classical information theory, compression of quantum information, transmission of quantum information through noisy channels, quantum error-correcting codes, quantum cryptography and teleportation. Overview of classical complexity theory, quantum complexity, efficient quantum algorithms, fault-tolerant quantum computation, physical implementations of quantum computation. Instructors: Kitaev, Preskill.

Ph/APh 223 ab. Advanced Condensed-Matter Physics. 9 units (3–0–6); *second, third terms. Prerequisites: Ph 125 or equivalent, or instructor's permission.* Advanced topics in condensed-matter physics, with emphasis on the effects of interactions, symmetry, and topology in many-body systems. Ph/Aph 223a covers second quantization, Hartree-Fock theory of the electron gas, Mott insulators and quantum magnetism, bosonization, quantum Hall effects, and symmetry protected topological phases such as topological insulators. Ph/Aph 223b will continue with BCS theory of superconductivity, Ginzburg-Landau theory, elements of unconventional and topological superconductors, theory of superfluidity, Bose-Hubbard model and bosonic Mott insulators, and some aspects of quantum systems with randomness. Instructors: Alicea, Motrunich.

Ph 229 abc. Advanced Mathematical Methods of Physics. 9 units (3–0–6); *first term. 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: Kapustin.

Ph 230 abc. Elementary Particle Theory. 9 units (3-0-6); 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. Instructor: Kapustin

Ph 236 abc. Relativity. 9 units (3-0-6); first, second 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. Not offered 2015–2016.

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 2015–16.

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 2015–16.

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 97. Undergraduate Research. *Units to be arranged; any term. Prerequisites: advanced political science and instructor's permission.* This course offers advanced undergraduates the opportunity to pursue research in political science individually or in a small group. Graded pass/fail.

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.* Instructor: Ordeshook

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); third 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. Two substantial papers are expected of students. Instructor: Alvarez.

PS 121. Analyzing Congress. *9 units (3-0-6); fall term.* Introduction to the US Congress with an emphasis on thinking analytically and empirically about the determinants of Congressional behavior. Among the factors examined are the characteristics and incentives of legislators, rules governing the legislative process and internal organization, separation of powers, political parties, Congressional elections, and interest group influence. Instructor: Hirsch.

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 2015-16.

PS 123. Regulation and Politics. 9 units (3-0-6); second 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. Not offered 2015–16.

An/PS 127. Corruption. 9 units (3-0-6). For course description, see Anthropology.

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 2015–16.

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. Instructor: Katz.

PS/SS 139. Comparative Politics. 9 units (3-0-6); second term. Prerequisites: PS 12. The politics of non-American political systems with an emphasis on their electoral systems and methodologies for assessing their compliance

with democratic standards. Students will be expected to develop data sets appropriate to analyzing elections in individual countries and offering an assessment of the pervasiveness of fraud in those elections. The student's grade will be determined by a final written report reporting the methodology and results of their analysis. Instructors: Ordeshook.

PS 141 ab. A History of Budgetary Politics in the United States. 9 units (3-0-6); *second, third terms.* 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. Instructors: 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. Prerequisites: Ec 11 or PS 12* This course is an introduction to non-cooperative game theory, with applications to political science and economics. It covers the theories of normal-form games and extensive-form games, and introduces solutions concepts that are relevant for situations of complete and incomplete information. The basic theory of repeated games is introduced. Applications are to auction theory and asymmetric information in trading models, cheap talk and voting rules in congress, among many others. Instructor: Tamuz.

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: Awipi.

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); *first 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.
Instructor: Tudusciuc.

Psy 25. Reading and Research in Psychology. *Units to be determined by the instructor. Not available for credit toward humanities–social science requirement.* Written report required. Graded pass/fail. Not offered 2015–16.

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.

Psy/CNS 105 ab. Frontiers in Neuroeconomics. *5 units (1.5–0–3.5); first term.* The new discipline of Neuroeconomics seeks to understand the mechanisms underlying human choice behavior, born out of a confluence of approaches derived from Psychology, Neuroscience and Economics. This seminar will consider a variety of emerging themes in this new field. Some of the topics we will address include the neural bases of reward and motivation, the neural representation of utility and risk, neural systems for intertemporal choice, goals vs habits, and strategic interactions. We will also spend time evaluating various forms of computational and theoretical models that underpin the field such as reinforcement-learning, Bayesian models and race to barrier models. Each week we will focus on key papers and/or book chapters illustrating the relevant concepts. Not offered 2015–16

Ec/Psy 109 ab. Frontiers in Behavioral Economics. *9 units (3–0–6).* *Prerequisites: Ec 11.* For course description, see Economics.

CNS/SS/Psy 110 abc. Cognitive Neuroscience Tools. *5 units (1.5–0–3.5).* 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.* Not offered 2015–16.

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 2015–16.

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/NB 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.

SS/Psy/CNS 285. Topics in Social, Cognitive, and Decision Sciences.

3 units (3-0-0); *first, second, third terms*. For course description, see Social Science.

SOCIAL SCIENCE

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. *Units to be determined by arrangement with the instructor; 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 (1.5-0-3.5). 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. Identification Problems in the Social Sciences. 9 units (3-0-6); *second term*. For course description, see Economics.

Ec/SS 129. Economic History of the United States. 9 units (3-0-6); *second term*. For course description, see Economics.

Ec/SS 130. Economic History of Europe from the Middle Ages to the Twentieth Century. 9 units (3-0-6); *third term*. For course description, see Economics.

PS/SS 139. Comparative Politics. 9 units (3-0-6); *second term*. 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.

SS/CS 149. Introduction to Algorithmic Economics. 9 units (3-0-6); *first term*. *Prerequisites: Ma 3, CS 24 and CS 38, or instructor permission.* This course will equip students to engage with current topics of active research at the intersection of social and information sciences, including: algorithmic

mechanism design; auctions; existence and computation of equilibria; and learning and games. Not offered 2015–16.

CS/SS 152. Introduction to Data Privacy. (3–0–6); *First. Prerequisites: Ma 3, CS 24 and CS 38, or instructor's permission.* For course description, see Computer Science.

CNS/Bi/SS/Psy/NB 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. Open to Social Science graduate students only. Instructors: Saito, Tamuz, 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. Open to Social Science graduate students only. Instructors: Hirsch, Katz, 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. Open to Social Science graduate students only. Instructors: Border, Echenique, Palfrey.

SS 209. Behavioral Economics. 9 units (3–0–6); *spring term. 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 2015–16.

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. Instructor: Yariv.

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. Instructors: Saito, Yariv.

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 2015–16.

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. Not offered 2015–16.

SS/Ma 214. Mathematical Finance. 9 units (3–0–6); *first term.* A course on pricing financial derivatives, risk management, and optimal portfolio selection using mathematical models. Students will be introduced to methods of Stochastic, Ito Calculus for models driven by Brownian motion. Models with jumps will also be discussed. Instructors: Cvitanic.

SS 215. Asset Pricing Theory. 9 units (3–0–6); *third term. Prerequisites: Students are recommended (but not required) to take SS/Ma 214.* This course is designed to get students familiar with modern research in asset pricing theory. It covers topics like arbitrage and pricing, mean-variance single period problem, arbitrage pricing theory, basics of continuous-time finance, valuation of assets in continuous-time and risk-neutral pricing, term structure results and considerations, intertemporal consumption-based asset pricing models, information economics, and some recent development in intermediary-based asset pricing models and behavioral asset pricing models. Instructors: Jin.

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 2015–16.

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. Not offered 2015–16.

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. Open to Social Science graduate students only. Instructor: Shum, Gillen, Sherman.

SS 223 abc. Advanced Topics in Econometric Theory. *9 units (3-0-6); first, second, third terms. Prerequisite: SS 222 abc; may be repeated for credit.* A course in quantitative methods for second- and third-year social science graduate students. Instructor: Sherman.

SS 225. Experiments. *9 units (3-0-6); first term.* This course explores the interaction of experimental design and econometric inference in the laboratory approach to economic questions. The course critically evaluates existing experimental studies to highlight this interaction and motivate consideration of inferential strategies early in an experiments design. Methodological topics may include testing theories in two-by-two designs, power and optimal design, classifying subjects into canonical types, testing based on elicited preferences and beliefs, and challenges introduced by communication and dynamics in economic experiments. Instructors: Agranov, Gillen.

SS 227. Empirical Methods in the Social Sciences. *9 units (3-0-6), second term. Prerequisites: 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. Instructor: Ewens.

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 2015–16.

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, Hoffman.

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. Not offered 2015–16.

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 2015–16.

SS/CS 241. Topics in Algorithmic Economics. *9 units (3-0-6). Prerequisites: SS/CS 149.* This is a graduate-level seminar covering recent topics at the intersection of computer science and economics. Topics will vary, but may include, e.g., dynamics in games, algorithmic mechanism design, and prediction markets. Instructors: EAS and HSS faculty. Not offered 2015–16.

CNS/SS 251. Human Brain Mapping: Theory and Practice. *9 units (2-1-6).* For course description, see Computation and Neural Systems.

SS/Psy/Bi/CNS 255. Topics in Emotion and Social Cognition. *9 units (3-0-6); third term. Prerequisite: Bi/CNS/NB 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 2015–16.

SS 260. Experimental Methods of Political Economy. *9 units (3-3-3); first, second, third terms.* Survey of laboratory experimental research related to the broad field of political economy. Topics: the behavior of markets, organiza-

tions, 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 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. Not offered 2015–16.

SS 282 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. Open to Social Science Graduate Students only. Instructor: Echenique.

SS/Psy/CNS 285. Topics in Social, Cognitive, and Decision Sciences. *3 units (3-0-0); first, second, third terms.* Select faculty will present their research background, methods, and a sampling of current questions/studies. Background readings and pdf of presentation will be provided. Instructors: Adolphs, Alvarez.

SS 300. Research in Social Science. *Units to be arranged.*

WRITING

Wr 1. Introduction to Academic Writing for Multilingual Writers. *9 units (3-0-6); first term.* This course offers a focused introduction to the practices of reading, thinking, and writing that characterize academic writing. More specifically, the course teaches students how to articulate a position, situate writing within specific contexts, engage with the work of others, locate and provide convincing evidence, and understand the expectations of different types of academic readers. Additionally, this course focuses on the challenges of academic writing that can be especially demanding for multilingual writers, including mastery of Academic English, understanding American academic conventions regarding citation and plagiarism, and being comfortable with American academic readers' expectations regarding argumentation and evidence. Students will take several writing projects through multiple stages of revision, improving their work with feedback from seminar discussions, workshops, and frequent one-to-one conferences with the instructor. Students are placed in Wr 1 based on a writing assessment that is required of all incoming students; successful completion of the course is required before taking freshman humanities courses. Enrolled students may be required to take Wr 3, 4, and/or 50 in subsequent quarters. Instructors: Hall, S.

Wr 2. Introduction to Academic Writing. *9 units (3-0-6); first term.* This course offers a focused introduction to the practices of reading, thinking, and writing that characterize academic writing. More specifically, the course

teaches students how to articulate a position, situate writing within specific contexts, engage with the work of others, locate and provide convincing evidence, and understand the expectations of different types of academic readers. Students will take several writing projects through multiple stages of revision, improving their work with feedback from seminar discussions, workshops, and frequent one-to-one conferences with the instructor. Students are placed in Wr 2 based on a writing assessment that is required of all incoming students; successful completion of the course is required before taking freshman humanities courses. Enrolled students may be required to take Wr 3, 4, and/or 50 in subsequent quarters. Instructors: Daley.

Wr 3. Reading and Composing Academic Writing. *9 units (3-0-6); second term.* This course builds on Wr 1 or 2 for students who need additional instruction in both the core concepts and practices of academic writing before beginning their freshman humanities coursework. The course will focus on developing critical reading skills and composing successful academic essays. By taking several writing projects through multiple stages of revision, students will develop a deeper sense of their strengths and limitations as writers, and seminar discussions, workshops, and frequent one-to-one conferences with the instructor will equip students to address those limitations. Not available for credit toward the humanities-social science requirement. Enrolled students may be required to take Wr 4 and/or 50 in subsequent quarters. Instructors: Hall, S.

Wr 4. Principles and Practices of Academic Writing. *3 units (1-0-2); second term.* Taken simultaneously with a freshman humanities course, this course offers weekly discussion of core concepts in academic writing. By focusing on the diverse scenes, situations, and genres of academic writing, the course aims to support writers both in their concurrent work writing in humanistic disciplines and to connect that learning to writing tasks that students will encounter in other academic locations. Not available for credit toward the humanities-social science requirement. Enrolled students also take Wr 50. Instructors: Hall, S.

Wr 50. Tutorial in Writing. *1-3 units to be arranged. By permission only.* Individualized tutorial instruction in writing and communication for students who benefit from weekly discussions about their work as writers. Not available for credit toward the humanities-social science requirement. Instructors: Hall, S.

En/Wr 84. Writing About Science. *9 units (3-0-6); third term.* For course description, see English.