

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

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|-----|---------------------------------------|------|--|
| Ae | Aerospace | FS | Freshman Seminars |
| AN | Anthropology | Ge | Geological and Planetary Sciences |
| ACM | Applied and Computational Mathematics | H | History |
| AM | Applied Mechanics | HPS | History and Philosophy of Science |
| APh | Applied Physics | Hum | Humanities |
| Art | Art History | IDS | Information and Data Sciences |
| Ay | Astrophysics | IST | Information Science and Technology |
| BMB | Biochemistry and Molecular Biophysics | ISP | Interdisciplinary Studies Program |
| BE | Bioengineering | L | Languages |
| Bi | Biology | Law | Law |
| BEM | Business, Economics and Management | MS | Materials Science |
| ChE | Chemical Engineering | Ma | Mathematics |
| Ch | Chemistry | ME | Mechanical Engineering |
| CE | Civil Engineering | MedE | Medical Engineering |
| CNS | Computation and Neural Systems | Mu | Music |
| CS | Computer Science | NB | Neurobiology |
| CMS | Computing and Mathematical Sciences | PVA | Performing and Visual Arts |
| CDS | Control and Dynamical Systems | PI | Philosophy |
| Ec | Economics | PE | Physical Education |
| EE | Electrical Engineering | Ph | Physics |
| EST | Energy Science and Technology | PS | Political Science |
| E | Engineering (General) | Psy | Psychology |
| En | English | SEC | Scientific and Engineering Communication |
| ESL | English As a Second Language | SS | Social Science |
| ESE | Environmental Science and Engineering | SA | Student Activities |
| F | Film | VC | Visual Culture |
| | | 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. Instructors: Austin, Colonius

Ae/AM/CE/ME 102 abc. Mechanics of Structures and Solids. *9 units (3-0-6); first, second, third terms. Prerequisites: ME 12 abc.* Introduction to continuum mechanics: kinematics, balance laws, constitutive laws with an emphasis on solids. Static and dynamic stress analysis. Two- and three-dimensional theory of stressed elastic solids. Wave propagation. Analysis of rods, plates and shells with applications in a variety of fields. Variational theorems and approximate solutions. Elastic stability. Instructors: Lapusta, Bhattacharya, Pellegrino.

Ae 103 ab. Aerospace Control Systems. *9 units (3-0-6); second and third terms. Prerequisites: CDS 110 (or equivalent), CDS 131 or permission of instructor.* Part a: Optimization-based design of control systems, including optimal control and receding horizon control. Introductory random processes and optimal estimation. Kalman filtering and nonlinear filtering methods for autonomous systems. Part b: Advanced astrodynamics, flight mechanics, and attitude dynamics. Guidance, navigation, and control of autonomous aerospace systems. Instructors: Chung.

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 process-

ing, 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. Space Engineering. 9 units (3-0-6) first term, (2-4-3) second term, (0-8-1) third term; first, second, third terms. Prerequisites: ME 11 abc and ME 12 abc or equivalent. Part a: Design of space missions based on astrodynamics. Topics include conic orbits with perturbations (J2, drag, and solar radiation pressure), Lambert's Theorem, periodic orbits and ground tracks, invariant manifolds, and the variational equation with mission applications to planetary flybys, constellation, formation flying, and low energy planetary capture and landing. Part b: Introduction to spacecraft systems and subsystems, mission design, rocket mechanics, launch vehicles, and space environments; spacecraft mechanical, structural, and thermal design; communication and power systems; 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 Instructor: Soon-Jo Chung.

CE/Ae/AM 108 ab. Computational Mechanics. 9 units (3-5-1). 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 2019–20.

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.
Instructor: Dimotakis

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 2019–20.

Ae 121 abc. Space Propulsion. 9 units (3-0-6); first, second, third terms. 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: Meiron.

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. Optical Engineering. 9 units (3-0-6); third term. Prerequisites: Ph 2, EE/Ae 157, or equivalent; APh 23 desirable. This class covers both the fundamentals of optical engineering and the development of space optical systems. Emphasis is on the design and engineering of optical, UV and IR systems for scientific remote sensing and imaging applications. Material covered is: first order optics to find the location, size and orientation of an image; geometrical aberration theory balancing tolerancing optical systems; transmittance, Etendu vignetting; radiative transfer; scalar vector wave propagation—physical optics; scalar diffraction image formation coherence; interferometry for the measurement of optical sur-

faces astronomy; optical metrology wavefront sensing control (A/O); segmented and sparse aperture telescopes; and design topics in coronagraphy, Fourier transform spectrometers, grating spectrometers, and large aperture telescopes. Space optics issues discussed will be segmented sparse aperture telescopes, radiation damage to glass, thermal and UV contamination. Instructor: Breckenridge.

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. Instructors: Lapusta, Ortiz.

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. Introduction and fabrication technology, elastic deformation of composites, stiffness bounds, on- and off-axis elastic constants for a lamina, elastic deformation of multidirectional laminates (lamination theory, ABD matrix), effective hygrothermal properties, mechanisms of yield and failure for a laminate, strength of a single ply, failure models, splitting and delamination. Experimental methods for characterization and testing of composite materials. Design criteria, application of design methods to select a suitable laminate using composite design software, hand layout of a simple laminate and measurement of its stiffness and thermoelastic coefficients. Not offered 2019–20.me

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 a. Advanced Fluid Mechanics. 9 units (3-0-6); second term. Prerequisites: Ae/APh/CE/ME 101 abc or equivalent; AM 125 abc or ACM/IDS 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. Not offered 2019–20.

Ae 204 ab. Technical Fluid Mechanics. 9 units (3-0-6); second, third terms. Prerequisite: Ae/APh/CE/ME 101 abc or equivalent. External and internal flow problems encountered in engineering, for which only empirical methods exist. Turbulent shear flow, separation, transition, three-dimensional and nonsteady effects. Basis of engineering practice in the design of devices such as mixers, ejectors, diffusers, and control valves. Studies of flow-induced oscillations, wind effects on structures, vehicle aerodynamics. Not offered 2019–20.

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 (AAReST). 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. Not offered 2019–20.

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: McKeon, Chung.

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); first 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. Not offered 2019–20.

Ae/AM/CE/ME 214 ab. Computational Solid Mechanics. 9 units (3-5-1); second, third terms. *Prerequisites: ACM 100 ab or equivalent; CE/AM/Ae 108 ab or equivalent or instructor's permission; Ae/AM/CE/ME 102 abc or Ae/Ge/ME 160 ab or instructor's permission.* Introduction to the use of numerical methods in the solution of solid mechanics and multiscale mechanics problems. First term: Variational principles. Finite element analysis. Variational problems in linear and finite kinematics. Time integration, initial boundary value problems. Elasticity and inelasticity. Constitutive modeling. Error estimation. Accuracy, stability and convergence. Iterative solution methods. Adaptive strategies. Second term: Multiscale modeling strategies. Computational homogenization in linear and finite kinematics. Spectral methods. Atomistic modeling and atomistic-to-continuum coupling techniques. Not offered 2019–20.

Ae/AM/ME 215. Dynamic Behavior of Materials. 9 units (3-0-6); third 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. Instructor: Ravichandran.

Ae/ME 218. Statistical Mechanics. 9 units (3-0-6); third 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. Instructor: Dimotakis.

Ae 220. Theory of Structures. 9 units (3-0-6); second term. *Prerequisites: Ae/AM/CE/ME 102 abc.* Fundamentals of buckling and stability, total potential energy and direct equilibrium approaches;

classification of instabilities into snap-through and bifurcations; eigenvalues and eigenvectors of stiffness matrix; Rayleigh-Ritz estimates of buckling loads; buckling of columns; imperfection sensitivity; elastic-plastic buckling; buckling of plates and shells. Selected topics: localization and wrinkling; design of imperfection insensitive shells and other topics. Instructor: Pellegrino.

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 2019-20.

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

Ae/AM/ME/Ge 225. Special Topics in Solid Mechanics. Units to be arranged; first, second, third terms. Subject matter changes depending on staff and student interest.

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. Instructors: Colonius, Meiron.

Ae 233. Hydrodynamic Stability. 9 units (3-0-6); second 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 2019–20.

Ae 234 ab. Hypersonic Aerodynamics. 9 units (3-0-6); second, third terms. *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 hyper-sonic 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 2019–20

Ae 235. Rarefied Gasdynamics. 9 units (3-0-6); first 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 2019–20.

Ae 237 ab. Nonsteady Gasdynamics. 9 units (3-0-6); second, third terms *Part a: dynamics of shock waves, expansion waves, and related discontinuities in gases.* Adiabatic phase-transformation waves. Interaction of waves in one- and two-dimensional flows. Boundary layers and shock structure. Applications and shock tube techniques. *Part b: shock and detonation waves in solids and liquids.* Equations of state for hydrodynamic computations in solids, liquids, and explosive reaction products. CJ and ZND models of detonation in solids and liquids. Propagation of shock waves and initiation of reaction in explosives. Interactions of detonation waves with water and metals. Not offered 2019–20.

Ae 239 ab. Turbulence. 9 units (3-0-6); second, third terms. *Prerequisites:* Ae/APh/CE/ME 101 abc; AM 125 abc or ACM/IDS 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. Not offered 2019–20.

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. Instructors: Meiron, Wincklemans.

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. Not Offered 2019–20.

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 2019–20.

MedE/BE/Ae 243. Physiological Mechanics. *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 bio-related 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 2019–20.

Ae 250. Reading and Independent Study. *Units to be arranged; first, second, third terms.* Graded pass/fail only.

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 2019–20.

Ae/AM/CE/ME/Ge 265 ab. Static and Dynamic Failure of Brittle Solids and Interfaces, from the Micro to the Mega. *9 units; (3-0-6); First, second. Prerequisites: Ae/AM/CE/ME 102 abc (concurrently) or equivalent and/or instructor's permission.* Linear elastic fracture mechanics of homogeneous brittle solids (e.g. geo-materials, ceramics, metallic glasses); small scale yielding concepts; experimental methods in fracture, fracture of bi-material interfaces with applications to composites as well as bonded and layered engineering and geological structures; thin-film and micro-electronic components and systems; dynamic fracture mechanics of homogeneous engineering materials; dynamic shear dominated failure of coherent and incoherent interfaces at all length scales; dynamic rupture of frictional interfaces with application to earthquake source mechanics; allowable rupture speeds regimes and connections to earthquake seismology and the generation of Tsunamis. Instructor: Rosakis.

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

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ANTHROPOLOGY

An 14. Introduction to Sociocultural Anthropology. *9 units (3-0-6); second 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 15. Human Evolution. *9 units (3-0-6); first term.* What makes humans unique and how did we evolve? This course will review 8 million years of hominin evolutionary history, focusing on the origins of defining features of our species including bipedalism, tool use, language, and advanced cognition. We will examine evidence from primatology and the genetic, fossil, and archaeological records. Concepts from evolutionary biology and anthropology will be covered including adaptation, phylogenetics, life history theory, behavioral ecology, and gene-culture coevolution. Instructor: Alex.

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.

An/PS 127. Corruption. *9 units (3-0-6); second term. Prerequisites: AN 14 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 and ethnic favoritism. How do we measure it? What are its costs and social consequences? What has culture got to do with it? How much does a free press matter? One antidote to corruption is better governance. Students will work closely with the professor to develop an independent and original research project analyzing a large dataset from Kenya. The goal is to understand why some regional governments in Kenya are better able to control this problem than others. Lessons learned should have global implications. 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. Not offered 2019–20.

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. Instructor: Staff.

ACM 80 abc. Undergraduate Thesis. 9 units; first, second, third terms. *Prerequisites:* 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 ACM faculty (or other faculty as approved by the ACM undergraduate option representative). Projects must include significant design effort. Written report required. Open only to upper class students. Not offered on a pass/fail basis. Instructor: Staff.

ACM 81 abc. Undergraduate Projects in Applied and Computational Mathematics. Units are assigned in accordance with work accomplished; first, second, third terms. *Prerequisites:* Consent of supervisor is required before registering. Supervised research or development in ACM by undergraduates. The topic must be approved by the project supervisor, and a formal final report must be presented on completion of research. Graded pass/fail. Instructor: 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: Pierce, Meiron.

ACM/IDS 101 ab. Methods of Applied Mathematics. 12 units (4-4-4); first, second terms. Prerequisites: Math 2/102 and ACM 95 ab or equivalent. 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, generalized eigenfunction expansions, convergence theory. Gibbs and Runge phenomena and their resolution. Chebyshev expansion and Fourier Continuation methods. Review of numerical stability theory for time evolution. Fast spectrally-accurate PDE solvers for linear and nonlinear Partial Differential Equations in general domains. Integral-equations methods for linear partial differential equation in general domains (Laplace, Helmholtz, Schrodinger, Maxwell, Stokes). Homework problems in both 101 a and 101 b include theoretical questions as well as programming implementations of the mathematical and numerical methods studied in class. Instructor: Bruno.

ACM/IDS 104. Applied Linear Algebra. 9 units (3-1-5); first term. Prerequisites: Ma 1 abc, some familiarity with MATLAB, e.g. ACM 11 is desired. This is an intermediate linear algebra course aimed at a diverse group of students, including junior and senior majors in applied mathematics, sciences and engineering. The focus is on applications. Matrix factorizations play a central role. Topics covered include linear systems, vector spaces and bases, inner products, norms, minimization, the Cholesky factorization, least squares approximation, data fitting, interpolation, orthogonality, the QR factorization, ill-conditioned systems, discrete Fourier series and the fast Fourier transform, eigenvalues and eigenvectors, the spectral theorem, optimization principles for eigenvalues, singular value decomposition, condition number, principal component analysis, the Schur decomposition, methods for computing eigenvalues, non-negative matrices, graphs, networks, random walks, the Perron-Frobenius theorem, PageRank algorithm. Instructor: Zuev.

ACM 105. Applied Real and Functional Analysis. 9 units (3-0-6); second term. Prerequisites: Ma 2, Ma 108a, ACM/IDS 104 or equivalent. This course is about the fundamental concepts in real and functional analysis that are vital for many topics and applications in mathematics, physics, computing and engineering. The aim of this course is to provide a working knowledge of functional analysis with an eye especially for aspects that lend themselves to applications. The course gives an overview of the interplay between different functional spaces and focuses on the following three key concepts: Hahn-Banach theorem, open mapping and closed graph theorem, uniform boundedness principle. Other core concepts

include: normed linear spaces and behavior of linear maps, completeness, Banach spaces, Hilbert spaces, L_p spaces, duality of normed spaces and dual operators, dense subspaces and approximations, hyperplanes, compactness, weak and weak* convergence. More advanced topics include: spectral theory, compact operators, theory of distributions (generalized functions), Fourier analysis, calculus of variations, Sobolev spaces with applications to PDEs, weak solvability theory of boundary value problems. Instructor: Hoffmann.

ACM/EE 106 ab. Introductory Methods of Computational Mathematics. *12 units (3-0-9); first, second 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. Instructors: Hosseini, Hou.

CMS/ACM/IDS 107. Linear Analysis with Applications. *12 units (3-3-6).* See course description in Computing and Mathematical Sciences.

ACM 109. Mathematical Modelling. *9 units (3-0-6); third term. Prerequisites: ACM 95/100 ab or equivalent.* This course gives an overview of different mathematical tools to analyze partial differential equations encountered across mathematics, biology, engineering and science. We will look at the main properties of different classes of linear and nonlinear PDEs and the behavior of their solutions using tools from functional analysis and calculus of variations with an emphasis on applications. We will discuss different types of reaction-diffusion systems, kinetic equations, advection and transport equations, the method of characteristics, gradient flows and entropy methods, conservation laws, population dynamics, parabolic equations and their spectral analysis, slow-fast dynamics, relaxation, asymptotic stability, blow-up and extinction of solutions, method of moments, instabilities and pattern formation, hydrodynamic scaling techniques and non-dimensionalisation. We will focus on representative models from different areas which may

include: Lotka-Volterra equations, the Fokker-Planck equation, the Boltzmann equation, the Fisher/KPP equation, Burger's equation, movement of cells and bacterial chemotaxis (Patlack-Keller-Segel model), SI models from epidemiology, predator-prey systems, chemical reactions, enzymatic reactions. The list is flexible and depends on the audience. If you are interested in this course, feel free to contact the instructor with (types of) models you would like to study. Instructor: Hoffmann.

Ec/ACM/CS 112. Bayesian Statistics. 9 units (3-0-6). See course description in Economics.

CMS/ACM/IDS 113. Mathematical Optimization. 12 units (3-0-9). See course description in Computing and Mathematical Sciences.

ACM/EE/IDS 116. Introduction to Probability Models. 9 units (3-1-5); first term. *Prerequisites:* Ma 3, some familiarity with MATLAB, e.g. ACM 11 is desired. This course introduces students to the fundamental concepts, methods, and models of applied probability and stochastic processes. The course is application oriented and focuses on the development of probabilistic thinking and intuitive feel of the subject rather than on a more traditional formal approach based on measure theory. The main goal is to equip science and engineering students with necessary probabilistic tools they can use in future studies and research. Topics covered include sample spaces, events, probabilities of events, discrete and continuous random variables, expectation, variance, correlation, joint and marginal distributions, independence, moment generating functions, law of large numbers, central limit theorem, random vectors and matrices, random graphs, Gaussian vectors, branching, Poisson, and counting processes, general discrete- and continuous-timed processes, auto- and cross-correlation functions, stationary processes, power spectral densities. Instructor: Zuev.

ACM 118. Stochastic Processes and Regression. 12 units (3-0-9); second term. *Prerequisites:* CMS/ACM/IDS 107 or equivalent, CMS 117 or equivalent, or permission of the instructor. Stochastic processes: Branching processes, Poisson point processes, Determinantal point processes, Dirichlet processes and Gaussian processes (including the Brownian motion). Regression: Gaussian vectors, spaces, conditioning, processes, fields and measures will be presented with an emphasis on linear regression. Kernel and variational methods in numerical approximation, signal processing and learning will also be covered through their connections with Gaussian process regression Instructor: Owadi.

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

Ma/ACM/IDS 140 ab. Probability. 9 units (3-0-6); second, third terms. For course description, see Mathematics.

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

ACM/IDS 154. Inverse Problems and Data Assimilation. 9 units (3-0-6); first term. *Prerequisites:* Basic differential equations, linear algebra, probability and statistics: ACM/IDS 104, ACM/EE 106 ab, ACM/EE/IDS 116, IDS/ACM/CS 157 or equivalent. Models in applied mathematics often have input parameters that are uncertain; observed data can be used to learn about these parameters and thereby to improve predictive capability. The purpose of the course is to describe the mathematical and algorithmic principles of this area. The topic lies at the intersection of fields including inverse problems, differential equations, machine learning and uncertainty quantification. Applications will be drawn from the physical, biological and data sciences. Instructor: Stuart.

IDS/ACM/CS 157. Statistical Inference. 9 units (3-2-4). For course description, see Information and Data Sciences.

IDS/ACM/CS 158. Fundamentals of Statistical Learning. 9 units (3-3-3). For course description, see Information and Data Sciences.

ACM/EE/IDS 170. Mathematics of Signal Processing. 12 units (3-0-9); third term. *Prerequisites:* ACM/IDS 104, CMS/ACM/IDS 113, and ACM/EE/IDS 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 2019–20.

CS/ACM 177 ab. Discrete Differential Geometry: Theory and Applications. 9 units (3-3-3). For course description, see Computer Science.

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

ACM 201. Partial Differential Equations. 12 units (4-0-8); first term. *Prerequisites:* ACM 95/100 ab, ACM/IDS 101 ab, ACM 11 or equivalent. This course offers an introduction to the theory of Partial Differential Equations (PDEs) commonly encountered across

mathematics, engineering and science. The goal of the course is to study properties of different classes of linear and nonlinear PDEs (elliptic, parabolic and hyperbolic) and the behavior of their solutions using tools from functional analysis with an emphasis on applications. We will discuss representative models from different areas such as: heat equation, wave equation, advection-reaction-diffusion equation, conservation laws, shocks, predator prey models, Burger's equation, kinetic equations, gradient flows, transport equations, integral equations, Helmholtz and Schrödinger equations and Stoke's flow. In this course you will use analytical tools such as Gauss's theorem, Green's functions, weak solutions, existence and uniqueness theory, Sobolev spaces, well-posedness theory, asymptotic analysis, Fredholm theory, Fourier transforms and spectral theory. More advanced topics include: Perron's method, applications to irrotational flow, elasticity, electrostatics, special solutions, vibrations, Huygens' principle, Eikonal equations, spherical means, retarded potentials, water waves, various approximations, dispersion relations, Maxwell equations, gas dynamics, Riemann problems, single- and double-layer potentials, Navier-Stokes equations, Reynolds number, potential flow, boundary layer theory, subsonic, supersonic and transonic flow. Not offered 2019–20.

ACM/IDS 204. Topics in Linear Algebra and Convexity. 9 units (3-0-6); second term. Prerequisites: ACM/IDS 104 and ACM/EE 106 a, CMS 117, or instructor's permission. Topic varies by year. 2019–20: Randomized algorithms for linear algebra. This class offers an introduction to the emerging field of randomized algorithms for solving linear algebra problems. Material may include trace estimation, norm estimation, matrix approximation by sampling, random projections, approximating least-squares problems, randomized SVD algorithms, approximate preconditioners, spectral computations, kernel methods, and fast linear system solvers. Assignments will require mathematical proofs, programming, and computer simulation. Instructor: Tropp.

ACM/IDS 213. Topics in Optimization. 9 units (3-0-6); first term. Prerequisites: ACM/IDS 104, CMS/ACM/IDS 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. Instructor: Chandrasekaran.

ACM/IDS 216. Markov Chains, Discrete Stochastic Processes and Applications. 9 units (3-0-6); second term. Prerequisites: ACM/EE/IDS 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/EE/IDS 217. Advanced Topics in Stochastic Analysis. 9 units (3-0-6); second term. Prerequisites: ACM/CMS/EE/IDS 117. 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 2019–20.

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

ACM 256. Special Topics in Applied Mathematics. 9 units (3-0-6); first term. Prerequisite: ACM/IDS 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 2019–20.

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 2019–20.

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.

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 (3-5-1).* 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 2019–20.

AM/CE/ME 150 abc. Graduate Engineering Seminar. *1 unit; each term; first, second, 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. Dynamics and Vibration. *9 units (3-0-6); first term.* 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 (Eigenvalue 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. Instructor: Asimaki.

AM/ME 165. Finite Elasticity. 9 units (3-0-6); third term. Prerequisites: Ae/Ge/ME 160 a. Finite theory of elasticity: constitutive theory, semi-inverse methods. Variational methods. Applications to problems of current interest. Not offered 2019–20.

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 ab. Computational Solid Mechanics. 9 units (3-5-1). 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/Ge 225. Special Topics in Solid Mechanics. Units to be arranged. For course description, see Aerospace.

AM/CE/ME 252. Linear and Nonlinear Waves in Structured Media. 9 units (2-1-6); second term. The course will cover the basic principles of wave propagation in solid media. It will discuss the fundamental principles used to describe linear and nonlinear wave propagation in continuum and discrete media. Selected recent scientific advancements in the dynamics of periodic media will also be discussed. Students learn the basic principles governing the propagation of waves in discrete and continuum solid media. These methods can be used to engineer materials with predefined properties and to design dynamical systems for a variety of engineering applications (e.g., vibration mitigation, impact absorption and sound insulation). The course will include an experimental component, to test wave phenomena in structured media. Instructor: Daraio.

Ae/AM/CE/ME/Ge 265 ab. Static and Dynamic Failure of Brittle Solids and Interfaces, from the Micro to the Mega. 9 units; (3-0-6). 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

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. APh/EE 9 ab. Instructor: Scherer. APh/EE 9b not offered 2019-20.

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 2019-20.

APh/EE 23. Demonstration Lectures in Classical and Quantum Photonics. 9 units (3-0-6); second term. Prerequisites: Ph 1 abc. This course covers fundamentals of photonics with emphasis on modern applications in classical and quantum optics. Classical optical phenomena including interference, dispersion, birefringence, diffraction, laser oscillation, and the applications of these phenomena in optical systems employing multiple-beam interferometry, Fourier-transform image processing, holography, electro-optic modulation, optical detection and heterodyning will be covered. Quantum optical phenomena like single photon emission will be discussed. Examples will be selected from optical communica-

tions, radar, adaptive optical systems, nano-photonic devices and quantum communications. Prior knowledge of quantum mechanics is not required. Instructor: Faraon.

APh/EE 24. Introductory Optics and Photonics Laboratory. 9 units (1-3-5); third term. *Prerequisites:* APh 23. Laboratory experiments to acquaint students with the contemporary aspects of optics and photonics 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. Not offered 2019–20.

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. APh/MS 105ab not offered 2019–20. APh/MS 105c Instructor: 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. Instructors: Troian, Ghaffari.

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

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

APh/Ph/Ae 116. Physics of Thermal and Mass Transport in Hydrodynamic Systems. 12 units (3-0-9); third 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. Instructor: Troian.

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

MS/APh 122. Diffraction, Imaging, and Structure. 9 units (0-4-5); first term. 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, Huyghens 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. Not offered 2019–20.

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 2019-20.

Ph/APh 137 abc. Atoms and Photons. 9 units (3-0-6). For course description, see Physics.

APh/Ph 138 ab. Quantum Hardware and Techniques. 9 units (3-0-6); *second and third terms*. *Prerequisites: Ph 125abc or Ph 127abc or Ph 137ab or instructor's permission*. This class covers multiple quantum technology platforms and related theoretical techniques, and will provide students with broad knowledge in quantum science and engineering. It will be split into three-week modules covering: applications of near-term quantum computers, superconducting qubits, trapped atoms and ions, topological quantum matter, solid state quantum bits, tensor-product states. APh/Ph 138a will not be offered 2019-20. APh/Ph 138b instructors: Endres, Faraon, Hsieh, Painter

EE/APh 149. Frontiers of Nonlinear Photonics. 9 units (3-0-6). For course description, see Electrical Engineering.

APh 150. Topics in Applied Physics. *Units and terms to be arranged*. Content will vary from year to year, but at a level suitable for advanced undergraduate or beginning graduate students. Topics are chosen according to the interests of students and staff. Visiting faculty may present portions of this course.

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: Nadj-Perge.

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. Not offered 2019–20.

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/MS 256. Computational Solid State Physics and Materials Science. 9 units (3-3-3); *third term*. *Prerequisites: Ph125 or equivalent and Aph114ab or equivalent*. The course will cover first-principles computational methods to study electronic structure, lattice vibrations, optical properties, and charge and heat transport in materials. Topics include: Theory and practice of Density Functional Theory (DFT) and the total-energy pseudopotential method. DFT calculations of total energy, structure, defects, charge density, bandstructures, density of states, ferroelectricity and magnetism. Lattice vibrations using the finite-difference supercell and Density Functional Perturbation Theory (DFPT) methods. Electron-electron interactions, screening, and the GW method. GW bandstructure

calculations. Optical properties, excitons, and the GW-Bethe Salpeter equation method. Ab initio Boltzmann transport equation (BTE) for electrons and phonons. Computations of heat and charge transport within the BTE framework. If time permits, selected advanced topics will be covered, including methods to treat vander Waals bonds, spin-orbit coupling, correlated materials, and quantum dynamics. Several laboratories will give students direct experience with running first-principles calculations. Not offered 2019–20.

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

(For course descriptions, please see Visual Culture page 735)

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. A field trip to Palomar Observatory will be organized. Not offered on a pass/fail basis. Instructor: Hallinan.

FS/Ay 3. Freshman Seminar: Automating Discovering the Universe. *6 units (2-0-4); second term.* For course description, see Freshman Seminar. Not offered 2019–20.

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. *9 units (3-1-5); 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: Ravi.

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: Steidel.

Ay 30. Introduction to Modern Research. 3 units (2-0-1); first 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: Hillenbrand.

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. Instructors: Howard, Steidel.

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. *Prerequisites:* 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. During the first term, the student should be fully engaged in and make significant progress on the research project. During second term, the research continues and an outline of the thesis itself should be reviewed with the advisor and the option representative. During third term, the research work is completed and the focus should turn to thesis writing. 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. 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. Instructor: Staff.

Ay 101. Physics of Stars. 9 units (3-0-6); first term. *Prerequisites:* 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: Fuller.

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: Hillenbrand.

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: Instructor: Kasliwal.

Ay 105. Optical Astronomy Instrumentation Lab. 9 units (1-5-3); *third term*. *Prerequisites:* 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 include radiometry measurements, geometrical optics, polarization, optical aberrations, spectroscopy, CCD characterization, vacuum and cryogenic technology, infrared detector technology, adaptive optics (wavefront sensors, deformable mirrors, closed loop control) and a coronagraphy tutorial. Instructor: Mawet.

Ay 111 a. Introduction to Current Astrophysics Research. 3 units; *second 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: Kirby.

Ge/Ay 117. Statistics and Data Analysis. 9 units (3-0-6). For course description, see Geological and Planetary Sciences.

Ay 119. Astroinformatics. 6 units (3-0-3); *third term*. This class is an introduction to the data science skills from the applied computer science, statistics, and information technology, that are needed for a modern research in any data-intensive field, but with a special focus on the astronomical applications. Open to graduate and upper-division on undergraduate students in all options. The topics covered include design of data systems, regression techniques, supervised and unsupervised machine learning, databases, Bayesian statistics, high performance computing, software carpentry, deep learning, and visualization. The class will feature real-world examples from cutting-edge projects in which the instructors are involved. Instructors: Djorgovski, Graham, Mahabal.

Ay 121. Radiative Processes. 9 units (3-0-6); *first term*. *Prerequisite:* Ph106bc, 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. Instructor: Phinney.

Ay 122 abc. Astronomical Measurements and Instrumentation. 9 units (3-0-6); *first, second terms*. *Prerequisites:* Ph 106bc or equivalent. Measurement and signal analysis techniques throughout the electromagnetic spectrum. Courses may include lab work and

field trips to Caltech observatories. Ay 122a concentrates on infra-red, optical, and ultraviolet techniques: telescopes, optics, detectors, photometry, spectroscopy, active/adaptive optics, coronagraphy. Imaging devices and image processing. Ay 122b concentrates on radio through submillimeter techniques: antennae, receivers, mixers, and amplifiers. Interferometers and aperture synthesis arrays. Signal analysis techniques and probability and statistics, as relevant to astronomical measurement. Ay 122c (not offered 2019–20) concentrates on X-ray through gamma-ray techniques. Instructors: Howard, Martin, Hallinan, Ravi.

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

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. Instructors: Kasliwal, Kulkarni.

Ay 126. Interstellar and Intergalactic Medium. 9 units (3-0-6); third 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: Kulkarni.

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

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

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

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

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

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. Astrobiology. 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 2019–20.

Ay/Ge 198. Special Topics in the Planetary Sciences. 9 units (3-0-6); *third term*. Topic for 2019–20 is Extrasolar Planets. Thousands of planets have been identified in orbit around other stars. Astronomers are now embarking on understanding the statistics of extra-solar 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: Howard, 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 2019–20.

Ay 215. Seminar in Theoretical Astrophysics. 9 units (3-0-6); *second term*. Course for graduate students and seniors in astronomy. Topic for 2019–20 will be compact binaries containing white dwarfs, neutron stars and black holes. Formation, mass transfer, accretion, X-ray and pulsar binaries, magnetic and wind interactions, mergers, gravitational waves. Students will be required to lead some discussions; homework will consist exclusively of reading and working through selected papers in preparation for discussions. Instructors: Fuller, Phinney.

Ay 218. Extrasolar Planets. 9 units (3-0-6); *third term*. Not offered 2019–20.

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 2019–20.

BIOCHEMISTRY AND MOLECULAR BIOPHYSICS

Bi/BE/BMB 115. Viruses and Applications to Biological Systems. 9 units (3-2-4). For course description, see Biology.

Ch/BMB 129. Introduction to Biophotonics. 9 units (3-0-6). For course description, see Chemistry.

BMB/Bi/Ch 170. Biochemistry and Biophysics of Macromolecules and Molecular Assemblies. 9 units (3-0-6); first term. 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. Not offered in 2019–20.

BMB/Bi/Ch 173. Biophysical/Structural Methods. 9 units (3-0-6); second term. 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, Jensen, and other guest lectures.

BMB/Bi/Ch 174. Advanced Topics in Biochemistry and Biophysics. 6 units (3-0-3); first term; Prerequisites: Bi/Ch 110 or equivalent. Discussion of research fields in biochemistry and molecular biophysics at Caltech. Instructors: Clemons, Hoelz, Shan and various guest lecturers.

BMB/Ch 178. Macromolecular Function: Kinetics, Energetics, and Mechanisms. 9 units (3-0-6); second 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, and enzyme evolution. 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-steadystate kinetics, kinetic simulations, and kinetics at the single molecule resolution. Instructor: Shan.

BMB/Ch 202 abc. Biochemistry Seminar Course. 1 unit; first, second, third terms. A course that includes a seminar on selected topics from outside faculty on recent advances in biochemistry. Students will participate in the seminar along with a formal discussion section with visiting faculty. 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: 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 Instructor: 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 2019–20.

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 and an overview of the courses offered in the Bioengineering option. Required for BE undergraduates. Graded pass/fail. Instructor: Staff.

Bi/BE 24. Scientific Communication for Biological Scientists and Engineers. *6 units (3-0-3).* 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 co-

advised 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. Not offered 2019–20.

BE/Bi 103 a. Introduction to Data Analysis in the Biological Sciences. 9 units (1-3-5); first term. *Prerequisites: Bi 1, Bi 1x, Bi 8, or equivalent; or instructor's permission.* This course covers tools needed to analyze quantitative data in biological systems. Students learn basic programming topics, data organization and wrangling, data display and presentation, basic image processing, and resampling-based statistical inference. Students analyze real data in class and in homework. Instructor: Bois.

BE/Bi 103 b. Statistical Inference in the Biological Sciences. 9 units (1-3-5); second term. *Prerequisites: BE/Bi 103 a or equivalent; Ma 1 abc and Ma 3, or Bi/CNS/NB 195, or equivalent; or instructor's permission.* This course introduces students to statistical modeling and inference, primarily taking a Bayesian approach. Topics include generative modeling, parameter estimation, model comparison, hierarchical modeling, Markov chain Monte Carlo, graphical display of inference results, and principled workflows. Other topics may also be included. All techniques are applied to real biological data sets in class and in homework. Instructor: Bois.

BE/Bi 106. Comparative Biomechanics. 9 units (3-0-6); second term. Have you ever wondered how a penguin swims or why a maple seed spins to the ground? How a flea can jump as high as a kangaroo? If spider silk is really stronger than steel? This class will offer answers to these and other questions related to the physical design of plants and animals. The course will provide a basic introduction to how engineering principles from the fields of solid and fluid mechanics may be applied to the study of biological systems. The course emphasizes the organismal level of complexity, although topics will relate to molecular, cell, and tissue mechanics. The class is explicitly comparative in nature and will not cover medically-related biomechanics. Topics include the physical properties of biological materials, viscoelasticity, muscle mechanics, biological pumps, and animal locomotion. Instructor: Dickinson. Not offered 2019–20.

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. Not offered 2019–20.

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

Bi/BE/BMB 115. Viruses and Applications to Biological Systems. 9 units (3-2-4). For course description, see Biology.

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

BE 150. Biological Circuit Design. 9 units (3-0-6); third term. Prerequisites: Bi 1, Bi 8, or equivalent; Ma 2, Bi/CNS/NB 195, or equivalent; or instructor's permission. Quantitative studies of cellular and developmental systems in biology, including the architecture of specific 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. The course will also consider the 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). 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 95/100 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 development 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 2 ab and ACM 95/100 ab, 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: Phillips.

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

MedE/EE/BE 168 abc. Biomedical Optics: Principles and Imaging. 9 units (4-0-5). For course description, see Medical Engineering.

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

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

Bi/BE/CS 183. Introduction to Computational Biology and Bioinformatics. 9 units (3-0-6). 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). For course description, see Chemical Engineering.

BE/EE/MedE 189 ab. Design and Construction of Biodevices. 189 a, 12 units (3-6-3) offered both first and third terms. 189b, 9 units (0-9-0) offered only third term. Prerequisites: BE/EE/MedE 189 a must be taken before BE/EE/MedE 189 b. Part a, students will design and implement computer-controlled biosensing systems, including a pulse monitor, a pulse oximeter, and a real-time polymerase-chain-reaction incubator. Part b is a student-initiated design project requiring instructor's permission for enrollment. Enrollment is limited to 24 students. Instructors: Bois, Yang.

BE/CS/CNS/Bi 191 ab. Biomolecular Computation. 9 units (3-0-6) second term; (2-4-3) third term. Prerequisites: 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. Not offered 2019–20.

BE/CS 196 ab. Design and Construction of Programmable Molecular Systems. 12 units; a (3-6-3) second term; b (2-8-2) third term. Prerequisites: none. 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 self-assembled DNA nanostructures, as well as quantitatively analyze the designs and the experimental data. Students will learn laboratory techniques including fluorescence spectroscopy and atomic force microscopy, and will use software tools and program in MATLAB or Mathematica. Part b is an open-ended design and build project. Enrollment in both parts a and b is limited to 12 students. Instructor: Qian. Not offered 2019–20.

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 201. Reading the Bioengineering Literature. 4 units (1-0-3); second term. Participants will read, discuss, and critique papers on diverse topics within the bioengineering literature. Offered only for Bioengineering graduate students. Instructor: K. Wang.

BE/Bi/NB 203. Introduction to Programming for the Biological Sciences Bootcamp. 6 units; summer term. *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 summer “boot camp” the week after Commencement, in which students spend all day working on the course. Students who do not have a strong need for the condensed boot camp schedule are encouraged to take BE/Bi 103a instead. Graded pass/fail. Instructor: Bois.

Bi/BE 222. The Structure of the Cytosol. 6 units (2-0-4). For course description, see Biology.

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

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

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

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

MedE/BE/Ae 243. Physiological Mechanics. 9 units (3-0-6). For course description, see Medical Engineering.

BE 262. Physical Biology Bootcamp. 12 units (2-10-0); summer term. *Prerequisites:* Enrollment limited to incoming Biology, Biochemistry and Molecular Biophysics, Bioengineering, and Neurobiology graduate students, or instructor’s permission. This course provides an intensive introduction to thinking like a quantitative biologist. Every student will build a microscope from scratch, use a confocal microscope to measure transcription in living fly

embryos and perform a quantitative dissection of gene expression in bacteria. Students will then use Python to write computer code to analyze the results of all of these experiments. No previous experience in coding is presumed, though for those with previous coding experience, advanced projects will be available. In addition to the experimental thrusts, students will use “street fighting mathematics” to perform order of magnitude estimates on problems ranging from how many photons it takes to make a cyanobacterium to the forces that can be applied by cytoskeletal filaments. These modeling efforts will be complemented by the development of physical models of phenomena such as gene expression, phase separation in nuclei, and cytoskeletal polymerization. Graded pass/fail. Instructor: Phillips.

Bi/BE/Ch/ChE/Ge 269. Integrative Projects in Microbial Science and Engineering. *6 units (3-0-3).* For course description, see Biology.

BIOLOGY

Bi 1. Principles of Biology—The great theories of biology and their influence in the modern world. *9 units (4-0-5); third term.*

There are three overarching theories in biology: the theory of the cell, the theory of the gene, and the theory of evolution. Each of them has had major impacts on our lives—for example the concept of the gene has led to treatments for inherited diseases, personalized and genomic medicine, forensic DNA testing, and modern agriculture. Each theory will be discussed from its 19th century origin to its standing in the 21st century, and the scientific understanding and societal impact of each will be sampled. The course will also ask if there is yet a theory of the brain, and if not, how one might be framed. The course is designed to teach what technically adept members of society should know about biology. Instructors: Meyerowitz, Zinn.

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: Regulation of Gene Expression. *9 units (3-0-6); 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. Assignments will include critical dissections of papers from classical and current research literature and problem sets. Instructors: Guttman, Hong.

Bi 9. Cell Biology. *9 units (3-0-6); third term. Prerequisites: Bi 8.* 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 ultra-structural and biochemical approaches to these topics. Instructors: Chan, Prober.

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.

Bi 21. Undergraduate Research with Presentation. *Minimum 12 units per term (0-11-1); first, second, third terms.* Special problems involving laboratory research in biology; to be arranged with instructors before registration. Must give a public presentation reporting results of work. May be counted as advanced lab credit. May be repeated for credit. Instructor: Staff.

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 or biological engineering, 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. Scientific 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 pro-

fessional 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 a 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 selected scientific topics, with feedback from instructors and peers. Fulfills the Institute scientific writing requirement. Instructor: MacLean.

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).* For course description, see Bioengineering.

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

BE/Bi 103 a. Introduction to Data Analysis in the Biological Sciences. *9 units (1-3-5).* For course description, see Bioengineering.

BE/Bi 103 b. Statistical Inference in the Biological Sciences. *9 units (1-3-5).* 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 2019–20.

BE/Bi 106. Comparative Biomechanics. 9 units (3-0-6); second 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, and the intermediary metabolism that provides energy to an organism. Instructor: Clemons.

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 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: Bjorkman, Yui.

Bi/BE/BMB 115. Viruses and Applications to Biological Systems. 9 units (3-2-4); third term. Learn about viruses as fascinating biological machines, focusing on naturally-occurring and evolved variants, in silico viral vector engineering, and computational methods that include structure visualization and machine learning. This course will introduce the fundamentals in the chemistry and biology of viruses, emphasizing their engineerable properties for use in basic research and translational applications. Topics include: viruses by the numbers, mammalian and non-mammalian (plant, bacteria)

viruses, enveloped vs. non-enveloped viruses, host-virus interactions, viral life cycles (replication vs. dormancy), immune responses to viruses, zoonosis, diverse mechanisms of entry and replication, the application of viruses as gene-delivery vehicles (with a focus on adeno-associated viruses or AAVs, lentiviruses, and rabies), and how to engineer viral properties for applications in basic research and gene therapy. The lectures will be complemented by short lab exercises in AAV preparation, bioinformatics and machine learning, and structure visualization. Instructors: Bjorkman, Gradinaru, Van Valen. Given in alternate years; offered 2019–20.

Bi 116. Microbial Genetics. 9 units (3-0-6); second term. *Prerequisites:* Bi 1, 8, 9 (or equivalent), and ESE/Bi 166. A course on microbial genetics, emphasizing the history of the discipline as well as modern approaches. Students will be exposed to different ways of manipulating microbial genomes (primarily bacterial, but we will also cover archaea and microbial eukaryotes). The power of microbial genetics to shed light on diverse process will be discussed in a variety of contexts, ranging from environmental science to the mammalian microbiome. Instructors: Mazmanian, Newman. Given in alternate years; offered 2019–20.

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. 9 units (3-0-6); second term. *Prerequisites:* Bi 8 and Bi 9, or instructor's permission. Lectures on and 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; adhesion/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. Students will choose term project involving writing a grant proposal or quantitative analysis of available datasets relating to lecture topics. Instructor: Stathopoulos. Given in alternate years; not offered 2019–20.

Bi 122. Genetics. 9 units (3-0-6); first term. *Prerequisite:* Bi 8 or Bi 9, or instructor's permission. Lecture and discussion course cover-

ing basic principles of genetics. Not open to freshmen. Instructors: Hay, Sternberg, Staff.

Bi/BE 129. The Biology and Treatment 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. The second part will concern newer information on cancer genetics and other topics, taught from the primary research literature. The last part of the course will concern treatments, including chemotherapy, anti-angiogenic therapy, and immunotherapy. Textbook: *The Biology of Cancer*, 2nd edition, by Robert Weinberg. Instructors: Zinn, Campbell. Given in alternate years; not offered 2019–20.

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

Bi 145 a. Tissue and Organ Physiology. 9 units (3-0-6); first term. *Prerequisites:* Bi 8, 9, Bi/Ch 110. *Bi/Ch 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 autonomic nervous system, urinary physiology, and the cardiovascular system. 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, the skeletal system, digestive and hepatic physiology, nutrition, 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/Psy 150. Introduction to Neuroscience. 10 units (4-0-6); third term. *Prerequisites:* Bi 8, 9, or instructor's 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. Letter grades only. Instructors: Adolphs, Lester.

Bi/CNS/NB 152. Neural Circuits and Physiology of Appetite and Body Homeostasis. 6 units (2-0-4); third term. *Prerequisites:* Graduate standing or Bi/CNS/NB/Psy 150, or equivalent. An advanced course of lectures, readings, and student presentations focusing on neural basis of appetites such as hunger and thirst. This course will cover the mechanisms that control appetites both at peripheral and central level. These include genetics, neural manipulation, and viral tracing tools with particular emphasis on the logic of how the body and the brain cooperate to maintain homeostasis. Instructor: Oka. Given in alternate years; not offered 2019–20.

Bi/CNS/NB 154. Principles of Neuroscience. 9 units (3-0-6); first term. *Prerequisites:* Bi/CNS/NB/Psy 150 or equivalent. This course aims to distill the fundamental tenets of brain science, unlike the voluminous textbook with a similar title. What are the essential facts and ways of understanding in this discipline? How does neuroscience connect to other parts of life science, physics, and mathematics? Lectures and guided reading will touch on a broad range of phenomena from evolution, development, biophysics, computation, behavior, and psychology. Students will benefit from prior exposure to at least some of these domains. Instructor: Meister. Given in alternate years; not offered 2019–20.

Bi/NB/BE 155. Neuropharmacology. 6 units (3-0-3); second term. *Prerequisites:* Bi/CNS/NB/Psy 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. Instructor: Lester. Given in alternate years; not offered 2019–20.

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. Instructor: Allman. Given in alternate years; not offered 2019–20.

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 2019–20.

Bi 160. Molecular Basis of Animal Evolution. 9 units (3-3-3); third term.

Prerequisites: Bi 8 and/or Bi 9 recommended. We share the planet with well over 1.5 million other animal species. This course covers how the staggering diversity of the animal kingdom came about through underlying molecular evolutionary phenomena, including gene and protein sequence evolution, gene family and genome evolution, the evolution of developmental processes, neural circuit evolution and behavior, and molecular mechanisms that physiologically adapt animals to their environment. Molecular processes involved in speciation will be explained, together with an analysis of constraints and catalysts on the production of selectable variation that have shaped the evolution of animal life. Participants will undertake a laboratory project on evolutionary genomics, involving fieldwork, genome sequencing and comparative genome analysis. The course focuses on the >99.9% of animals that lack backbones. Instructor: Parker.

PI/CNS/NB/Bi/Psy 161. Consciousness. 9 units (3-0-6). For

course description, see Philosophy.

Bi/CNS/NB 162. Cellular and Systems Neuroscience Laboratory. 12 units (2-4-6); second term. *Prerequisites:* Bi/CNS/NB/Psy 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 vertebrate and invertebrate brains, using extra- and intracellular recording techniques. Students are instructed in all aspects of experimental procedures, including proper surgical techniques, electrode fabrication, and data analysis. The class also includes a brain dissection and independent student projects that utilize modern digital neuroscience resources. Instructor: Bremner.

NB/Bi/CNS 163. The Biological Basis of Neural Disorders. 6

units (3-0-3); second term. For course description, see Neurobiology.

Bi/CNS/NB 164. Tools of Neurobiology. 9 units (3-0-6); first term. Prerequisites: Bi/CNS/NB/Psy 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. The course will serve to introduce graduate students to 1) the process of writing fellowships to train students in preparing effective funding applications; 2) ongoing research projects on campus involving the isolation, culture, and characterization of microbes and microbial communities as well as projects in other fields; and 3) presentation of research and asking questions in research presentations. The first half of the class will involve training in grant writing by drafting an NSF-GRFP proposal. The second half of the class will involve giving chalk talk research presentations. Students can apply from all departments; priority will be given to those in microbiology. Enrollment is limited to instructor approval. Instructor: Hoy.

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). For course description, see Biochemistry and Molecular Biophysics.

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

BMB/Bi/Ch 174. Advanced Topics in Biochemistry. 6 units (3-0-3). For course description, see Biochemistry and Molecular Biophysics.

CNS/Bi/Psy/NB 176. Cognition. 9 units (4-0-5). 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 micro-

scopes. 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. Instructor: Collazo. Given in alternate years; not offered 2019–20.

Ge/ESE/Bi 178. Microbial Ecology. 9 units (3-2-4). For course description, see Geological and Planetary Sciences.

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/Ch 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. Given in alternate years; offered 2019–20.

Bi/BE/CS 183. Introduction to Computational Biology and Bioinformatics. 9 units (3-0-6); second term. Prerequisites: Bi 8, CS 2, Ma 3; or BE/Bi 103a; 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 data sets. Instructors: Pachter, Thomson.

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. We 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. An important aspect of the course is the lab component in which students design and analyze their own fMRI experiment. Instructor: Tsao. Given in alternate years; not offered 2019–20.

Bi/CNS/NB 185. Large Scale Brain Networks. 6 units (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, not offered 2019–20.

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. Instructor: Wold. Given in alternate years; offered 2019–20.

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

Bi 190. Systems Genetics. 6 units (2-0-4); first 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. Given in alternate years; not offered 2019–20.

BE/CS/CNS/Bi 191 ab. Biomolecular Computation. 9 units (3-0-6). 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. Instructor: Goentoro.

Bi/CNS/NB 195. Mathematics in Biology. 9 units (3-0-6); first term. *Prerequisites:* 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.

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

Bi 206. Biochemical and Genetic Methods in Biological Research. 6 units (2-0-4); third term. *Prerequisites:* graduate standing. This course will comprise discussions of selected methods in molecular biology and related fields. Instructor: Varshavsky. Given in alternate years; offered 2019–20.

Bi 214. Stem Cells and Hematopoiesis. 9 units (3-0-6); third term. *Prerequisites:* Graduate standing, or at least one of Bi 114, Bi 117, Bi/Be 182, plus molecular biology. An advanced course with classes based on active discussion, lectures, and seminar presentations. Development from embryos and development from stem

cells are distinct paradigms for understanding and manipulating the emergence of ordered biological complexity from simplicity. This course focuses on the distinguishing features of stem-cell based systems, ranging from the natural physiological stem cells that are responsible for life-long hematopoiesis in vertebrates (hematopoietic stem cells) to the artificial stem cells, ES and iPS cells, that have now been created for experimental manipulation. Key questions will be how the stem cells encode multipotency, how they can enter long-term self-renewal by separating themselves from the developmental clock that controls development of the rest of the organism, and how the self-renewal programs of different stem cell types can be dismantled again to allow differentiation. Does “stemness” have common elements in different systems? The course will also cover the lineage relationships among diverse differentiated cell types emerging from common stem cells, the role of cytokines and cytokine receptors in shaping differentiation output, apoptosis and lineage-specific proliferation, and how differentiation works at the level of gene regulation and regulatory networks. Instructor: Rothenberg.

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 2019–20.

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. Instructor: Allman. Given in alternate years; not offered 2019–20.

Bi/CNS/NB 220. Genetic Dissection of Neural Circuit Function.

6 units (2-0-4); second term. *Prerequisites:* Bi/CNS/NB/Psy 150 or equivalent. *Open to advanced (junior or senior) undergraduates only and with instructor permission.* 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 CNS or other graduate 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. Not offered 2019–20.

Bi/BE 222. The Structure of the Cytosol. 6 units (2-0-4); third term. Prerequisites: Bi 9, Bi/Ch 110-111 or graduate standing in a biological discipline. The cytosol, and fluid spaces within the nucleus, were once envisioned as a concentrated soup of proteins, RNA, and small molecules, all diffusing, mixing freely, and interacting randomly. We now know that proteins in the cytosol frequently undergo only restricted diffusion and become concentrated in specialized portions of the cytosol to carry out particular cellular functions. This course consists of lectures, reading, student presentations, and discussion about newly recognized biochemical mechanisms that confer local structure and reaction specificity within the cytosol, including protein scaffolds and “liquid-liquid phase separations that form “membraneless compartments.” Instructor: Kennedy.

Bi/BE 227. Methods in Modern Microscopy. 12 units (2-6-4); second term. Prerequisites: Bi/BE 177 or a course in microscopy. 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. Enrollment is limited. Instructor: Collazo. Given in alternate years; offered 2019–20.

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/Psy 150 or equivalent or instructor's permission. 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. The class offers weekly hands-on LAB exposure for opsin viral production and delivery to neurons, recording of light-modulated activity, and tissue clearing, imaging, and 3D reconstruction of fluorescent samples. Lecture topics include: opsin design (including natural and artificial sources), delivery (genetic targeting, viral transduction), light activation requirements

(power requirements, wavelength, fiberoptics), 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 of these methods to neuronal circuits (case studies based on recent literature). Instructor: Gradinaru. Given in alternate years; offered 2020-21.

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. Prerequisites: 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. Instructors: Aravin, Voorhees.

Bi 250 b. Topics in Systems Biology. 9 units (3-0-6); *third term. Prerequisites: Bi 1, Bi 8, or equivalent; Ma 2, Bi/CNS/NB 195, or equivalent; or instructor's permission.* Quantitative studies of cellular and developmental systems in biology, including the architecture of specific 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. The course will also consider the organization of transcriptional and protein-protein interaction networks at the genomic scale. Topics are approached from experimental, theoretical, and computational perspectives. 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.

Bi 253. Reading, Writing, Reviewing, Experimental Design and Reproducibility. 6 units (2-0-4); *second term.* This course will consider scholarly communication in molecular and cellular biology, broadly defined. Students will learn about data standards, the minimal information required to describe an experiment and computer code. Discussion will include long term storage of data and informatics workflows. Appropriate citation of other article and resources will be considered. We will discuss evaluation of scientific premise, rigorous experimental design and interpretation, appropriate statistical power, authentication of key biological and chemical resources, data and material sharing, record keeping, and transparency in reporting data and observations. Students will learn to read papers critically and practice reviewing short articles from Micro-publication: biology, which are short enough to allow a thorough analysis of methods necessary to ensure reproducibility. Graded Pass/Fail. Instructors: Sternberg, Hay, Meister, Staff.

Ch/Bi 253. Advanced Topics in Biochemistry. 6 units (2-0-4). For course description, see Chemistry.

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

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

Bi/BE/Ch/ChE/Ge 269. Integrative Projects in Microbial Science and Engineering. 6 units (3-0-3); *second term*. A project-based course designed to train students to integrate biological, chemical, physical and engineering tools into innovative microbiology research. Students and faculty will brainstorm to identify several “grand challenges” in microbiology. Small teams, comprised of students from different graduate programs and disciplinary backgrounds (e.g. a chemical engineer, a computer scientist and a biologist) and a faculty member, will work to compose a project proposal addressing one of the grand challenges, integrating tools and concepts from across disciplines. Student groups will present draft proposals and receive questions and critiques from other members of the class at check-in points during the academic term. While there will not be an experimental laboratory component, project teams may tour facilities or take field trips to help define the aims and approaches of their projects. At the end of the course, teams will deliver written proposals and presentations that will be critiqued by students and faculty. Instructor: CEMI Faculty.

Bi 270 abc. Special Topics in Biology. *Units to be arranged each term; first, second, third.* 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

520

BEM/EC/PS 80. Frontiers in Social Sciences. 1 unit (1-0-0); *first term*. Weekly seminar by a member of the Caltech Social Sciences faculty to discuss a topic of their current research or teaching at an introductory level. The course can be used to learn more about different areas of study and about undergraduate courses within the Social Sciences. The course will also be useful to those interested in pursuing the BEM, EC or PS options, or participating in research (SURF, for example) under supervision of the Social Science faculty. Graded pass/fail. Instructor: Cvitanic.

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 determined by instructor. Instructors: Staff, visiting lecturers.

BEM 102. Introduction to Accounting. *9 units (3-0-6); third term.* This course provides the knowledge and skills necessary for the student to understand financial statements and financial records and to make use of the information for management and investment decisions. Topics include: an overview of financial statements and business decisions; the balance sheet, the income statement, and the cash flow statement; sales revenue, receivables, and cash; cost of goods sold and inventory; long-lived assets and depreciation, and amortization; current and long-term liabilities; owners' equity; investments in other corporations and an introduction to financial statement analysis. Instructor: Ewens.

BEM 103. Introduction to Finance. *9 units (3-0-6); second term. Prerequisites: Ec 11 required; Ma 1 abc recommended (to be familiar with calculus and linear algebra).* Finance, or financial economics, covers two main areas: asset pricing and corporate finance. For asset pricing, a field that studies how investors value securities and make investment decisions, we will discuss topics like prices, risk, and return, portfolio choice, CAPM, market efficiency and bubbles, interest rates and bonds, and futures and options. For corporate finance, a field that studies how firms make financing decisions, we will discuss topics like security issuance, capital structure, and firm investment decisions (the net present value approach, and mergers and acquisitions). In addition, if time permits, we will cover some topics in behavioral finance and household finance such as limits to arbitrage and investor behavior. Instructor: Jin.

BEM 104. Investments. *9 units (3-0-6); third 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: Roll.

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. Since 2015, the course is offered in the flipped format: the students are required to watch lectures online, while problem solving and case and paper presentations are done in class. Instructor: Cvitanic.

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. Not offered 2019–20.

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. Not offered 2019–20.

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. Instructor: Ewens.

BEM 111. Quantitative Risk and Portfolio Management. 9 units (3-0-6); second 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 112. International Financial Markets. 9 units (3-0-6); second term. Prerequisites: BEM 103 or instructor permission. The course offers an introduction to international financial markets, their comparative behavior, and their inter-relations. The principal focus will be on assets traded in liquid markets: currencies, equities, bonds, swaps, and other derivatives. Attention will be devoted to (1) institutional arrangements, taxation, and regulation, (2) international arbitrage and parity conditions, (3) valuation, (4) international diversification and portfolio management, (5) derivative instruments, (6) hedging, (7) dynamic investment strategies, (8) other topics of particular current relevance and importance. Not offered 2019–20.

BEM 117. 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/ESE 119. Environmental Economics. 9 units (3-0-6); first term. Prerequisites: Ec 11 or equivalent. This course provides a survey from the perspective of economics of public policy issues regarding the management of natural resources and the protection of environmental quality. The course covers both conceptual topics and recent and current applications. Included are principles of environmental and resource economics, management of nonrenewable and renewable resources, and environmental policy with the focus on air pollution problems, both local problems (smog) and global problems (climate change). Instructor: Ledyard.

BEM/Ec 150. Business Analytics. 9 units (3-0-6); first 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. Not offered 2019–20.

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 units (1-4-4); first term. Prerequisites: Ma 2 (may be taken concurrently). Introduction to the solution of engineering problems through the use of the computer. Elementary programming in Python 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); second term. Prerequisites: ChE 15 and Ma 2. 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. 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: Gavalas, Ismagilov.

ChE 70. Special Topics in Chemical Engineering. Units by arrangement; terms to be arranged; offered by announcement. Prerequisites: instructor's permission. Special problems or courses arranged to meet the emerging needs of undergraduate students. May be repeated for credit, as content may vary. Grading scheme at instructor's discretion. Instructors: to be determined.

ChE 80. Undergraduate Research. Units by arrangement, instructor's permission required. Research in chemical engineering offered as an elective in any term. Graded pass/fail. Instructor: Staff.

ChE 90 abc. 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. In addition, students must submit a midterm progress report in each term, end-of-term progress reports at the end of the first two terms, and a thesis draft in the third term. A grade will not be assigned prior to completion of the thesis, which normally takes three terms. A P grade will be given for the first two terms 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: Davis.

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: Kornfield, Shapiro, Flagan.

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. NMR characterization methods in the areas of heterogeneous catalysts, batteries, energy storage materials, etc. will be reviewed. More specific topics include NMR methods in solid state such as magic angle spinning (MAS), cross-polarization (CP), NMR of quadrupole nuclei, multiple pulse and multi-dimensional solid state NMR experiments, dynamics NMR. Hands-on experience will be provided via separate laboratory sessions using solid NMR spectrometers at Caltech Solid State NMR facility. Instructor: Hwang.

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 2019–20.

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

ChE 120. Optimal Design of Chemical Systems. 9 units (1-6-2); third term. Prerequisites: ChE 63 ab, ChE 101, ChE 103 abc, ChE 126, or instructor's permission. Short-term, open-ended projects that require students to design and build a chemical process or

manufacture a chemical product. Each team selects a project after reviewing a collection of proposals. Students use chemical engineering principles to design, build, test, and optimize a system, component, or product that fulfills specified performance requirements, subject to constraints imposed by budget, schedule, logistics, environmental impact, safety, and ethics. Instructor: Vicic.

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

ChE 128. Chemical Engineering Design Laboratory. 9 units (1-6-2); second term. Prerequisites: ChE 63 ab, ChE 101, ChE 103 abc, or instructor's permission. Short-term, open-ended research projects targeting chemical processes in microreactors. Projects include synthesis of chemical products or nanomaterials, 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, Vicic.

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. Students will propose and execute research projects in biomolecular engineering and synthetic biology. Emphasis will be on projects that apply rational or library-based design strategies to the control of system behavior. Instructors: Davis, Vicic.

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

ChE 141. Data Science for Chemical Systems. 9 units (1-2-6); second term. Prerequisites: ChE 15, ACM/IDS 104. Through short lectures, in-class activities, and problem sets, students learn and use methods in data science to complete projects focused on

(i) descriptive and predictive analyses of chemical processes and (ii) Quantitative Structure Property Relationships (QSPR). Topics covered may include six sigma; SPC & SQC; time-series analysis; data preprocessing; dimensionality reduction; supervised, reinforcement, and unsupervised learning; decision tree & clustering methods; univariate and multivariate regression; and visualization. Python is the programming language of instruction. Instructor: Vicic.

ChE 142. Challenges in Data Science for Chemical Systems. 9 units (1-0-8); third term. *Prerequisites:* ChE 141. Student groups complete a one-term, data-science project that addresses an instructor-approved chemical engineering challenge. The project may be an original research idea; related to work by a research group at the Institute; an entry in a relevant national/regional contest; a response to an industry relationship; or other meaningful opportunity. There is no lecture, but students participate in weekly progress updates. A student may not select a project too similar to research completed to fulfill requirements for ChE 80 or ChE 90abc. Instructor: Vicic.

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 the structure and dynamics of polymeric liquids, 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, a chain under different solvent conditions; dilute and semi-dilute solutions; thermodynamics of polymer blends and block copolymers; polyelectrolytes; rubber elasticity; polymer gels; linear viscoelasticity of polymer solutions and melts. Instructor: Wang. Not offered 2019–20.

ChE 151 ab. Physical and Chemical Rate Processes. 12 units (3-0-9); second, third 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. *Prerequisites:* ChE 101 or instructor's permission. Survey of heterogeneous reactions on metal and oxide catalysts. Langmuir-Hinshelwood versus Eley-Rideal reaction

mechanisms. Reaction, diffusion, and heat transfer in heterogeneous catalytic systems. Characterization of porous catalysts. Instructor: Giapis.

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 2019–20.

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 8, 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 (Python is the language of instruction). 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. Instructor: Wang.

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); first 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 and active matter. Other topics may be discussed depending on class needs and interests. Instructor: Brady.

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. Not offered 2019–20.

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. Instructor: Staff.

Bi/BE/Ch/ChE/Ge 269. Integrative Projects in Microbial Science and Engineering. 6 units (3-0-3). For course description, see Biology.

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; 9 units; a (3-0-3) first term; b (4-0-5) second term. Lectures and recitations dealing with the principles of chemistry. First term: Chemical bonding—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 dynamics—spectroscopy, thermodynamics, kinetics, chemical equilibria, electrochemistry, and introduction to organic chemistry. Graded pass/fail. Instructors: Lewis (a), Robb, Miller (b).

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. Freshmen who enter in academic years 2017, 2018, and 2019 must take Ch 3 a in their first nine terms of residence in order to be graded pass/fail. Freshmen entering in academic year 2020 and thereafter must take Ch 3 a in their first six terms of residence in order to be 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, photochemistry, and photoelectrochemistry, culminating in the construction and testing of dyesensitized solar cells. Freshmen who enter in academic years 2017, 2018, and 2019 must take Ch 3x in their first nine terms of residence in order to be graded pass/fail. Freshmen entering in academic year 2020 and thereafter must take Ch 3x in their first six terms of residence in order to be graded pass/fail. 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 organome-

tallic 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 2019–20.

Ch 6 ab. Physical and Biophysical Chemistry Laboratory. *9 units (1-5-3); second, third terms. Prerequisites: Ch 1, Ch 4 ab, and Ch 21 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. Part b not offered 2019–20. Instructor: Okumura.

Ch 7. Advanced Experimental Methods in Bioorganic Chemistry. *9 units (1-6-2); third term. Prerequisites: Ch 41 abc, and Bi/Ch 110, Ch 4 ab. Enrollment by instructor's permission.* Preference will be given to students who have taken Ch 5 a or Bi 10. This advanced laboratory course will provide experience in 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. Instructor: Hsieh-Wilson.

Ch 8. Experimental Procedures of Synthetic Chemistry for Premedical Students. *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.* Open to non-pre-medical students, as space allows. Introduction to methods of extraction, synthesis, separation and purification, and spectroscopic characterization of Aspirin, Tylenol, and medical test strips. 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 organometallic compounds. Specific emphasis will be focused on following the scientific method in the study of model organic and inorganic materials. Enrollment priority given to chemical engineering majors. Instructor: Mendez.

Ch 10 abc. Frontiers in Chemistry. 1 unit (1-0-0) first, second terms; 6 units (1-4-1) third term. Prerequisites: Open for credit to freshmen and sophomores. 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. 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. 9 units (3-0-6); second term. This course will cover acid-base equilibria, complex ion formation, chelation, oxidation-reduction reactions, and partitioning equilibria. These topics will serve as the basis for introducing separation techniques such as gas and liquid chromatography and the hyphenated techniques associated with them (GC-MS, LC-MS, etc.) Laboratory activities will be integrated with the course topics. Instructor: Rees.

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

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

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 recommended. Develops the basic principles of solution thermodynamics, transport processes, and reaction kinet-

ics, with emphasis on biochemical and biophysical applications.
Instructor: Not offered 2019–20.

Ch 41 abc. Organic Chemistry. 9 units (4-0-5); first, second, third terms. Prerequisites: Ch 1 ab or instructor's permission. The synthesis, structure, and mechanisms of reactions of organic compounds. Instructors: Grubbs (a), Hsieh-Wilson (b), Reisman (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. Senior Thesis Research. 9 units; first, second, third terms. Prerequisites: Instructor's permission. Three terms of Ch 82 are to be completed during the junior and/or senior year of study. At the end of the third term, 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. An oral thesis defense will be arranged by the CUSC in the third term for all enrollees. The first two terms of Ch 82 will be taken on a pass/fail basis, and the third term will carry a letter grade. Instructors: Okumura, staff.

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. Class size limited to 12 students. Instructor: Bikle.

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

Ch 101. Chemistry Tutorials. 3 units (1-0-2); third term. Small group study and discussion on special areas of chemistry, chemical engineering, molecular biology, or biophysics. Instructors drawn from advanced graduate students and postdoctoral staff will lead weekly tutorial sessions and assign short homework assignments,

readings, or discussions. Tutorials to be arranged with instructors before registration. Instructors: Staff.

Ch 102. Introduction to Inorganic Chemistry. 9 units (4-0-5); third term. *Prerequisites:* Ch 41 ab. Structure and bonding of inorganic species with special emphasis on spectroscopy, ligand substitution processes, oxidation-reduction reactions, organometallic, biological inorganic chemistry, and solid-state chemistry. Instructors: Hadt, See.

Ch 104. Intermediate Organic Chemistry. 9 units (4-0-5); second term. *Prerequisites:* Ch 41 abc. A survey of selected topics beyond introductory organic chemistry, including reaction mechanisms and catalysis. Instructor: Fu.

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. *Prerequisites:* Ch 102 or instructor's permission. Introduction to group theory, ligand field theory, and bonding in coordination complexes and organotransition metal compounds. Systematics of bonding, reactivity, and spectroscopy of commonly encountered classes of transition metal compounds. Instructors: Agapie, Hadt.

Ch 117. Introduction to Electrochemistry. 9 units (3-0-6); first term. Discussion of the fundamentals and applications of electrochemistry with an emphasis on the structure of electrode-electrolyte interfaces, the mechanism by which charge is transferred across it, experimental techniques used to study electrode reactions, and application of electrochemical techniques to study materials chemistry. Topics may vary but usually include diffusion, cyclic voltammetry, coulometry, irreversible electrode reactions, the electrical double layer, and kinetics of electrode processes. Instructor: See.

Ch 120 ab. Nature of the Chemical Bond. Ch 120 a: 9 units (3-0-6), third term; Ch 120 b: (1-1-7), first 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) third term. Prerequisites: Ch 21 a or Ch 125 a.* Application of Atomistic-based methods [Quantum Mechanics (QM) and Molecular Dynamics (MD)] for predicting the structures and properties of molecules and solids and simulating the dynamical properties. This course emphasizes hands-on use of modern commercial software (such as Jaguar for QM, VASP for periodic QM, and LAMMPS for MD) for practical applications and is aimed at experimentalists and theorists interested in understanding structures, properties, and dynamics in such areas as biological systems (proteins, DNA, carbohydrates, lipids); polymers (crystals, amorphous systems, co-polymers); semiconductors (group IV, III-V, surfaces, defects); inorganic systems (ceramics, zeolites, superconductors, and metals); organo-metallics, and catalysis (heterogeneous, homogeneous, and electrocatalysis). Ch121a covers the basic methods with hands-on applications to systems of interest using modern software. The homework for the first 5 weeks emphasizes computer based solutions. For the second 5 weeks of the homework each student proposes a short research project and uses atomistic simulations to solve it. Ch121b 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 125 abc. The Elements of Quantum Chemistry. *9 units (3-0-6); first, second, third terms. Prerequisites: Ch 21 abc or an equivalent brief introduction to quantum mechanics.* A treatment of quantum mechanics with application to molecular and material systems. The basic elements of quantum mechanics, the electronic structure of atoms and molecules, the interactions of radiation fields and matter, and time dependent techniques relevant to spectroscopy will be covered. The course sequence prepares students for Ch 225 and 226. Instructors: Cushing (a), Weitekamp (b), part (c) not offered 2019–20.

Ch 126. Molecular Spectra and Molecular Structure. 9 units (3-0-6); third term. Prerequisites: Ch 21 and Ch 125 a/Ph 125 a 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, density matrices, linear and nonlinear interactions of radiation and matter. Instructor: Blake. Not offered 2019–20.

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. For course description, see Geological and Planetary Sciences.

Ch/BMB 129. Introduction to Biophotonics. 9 units (3-0-6); first term. Prerequisites: Ch 21abc required. Ch 125, 126 recommended. This course will cover basic optics and introduce modern optical spectroscopy principles and microscopy techniques. Topics include molecular spectroscopy; linear and nonlinear fluorescence microscopy; Raman spectroscopy; coherent microscopy; single-molecule spectroscopy; and super-resolution imaging. Instructor: Wei. Not offered 2019–20.

Ch 135. Chemical Dynamics. 9 units (3-0-6); third 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. Not offered 2019–20.

Ch/ChE 140 ab. Principles and Applications of Semiconductor Photoelectrochemistry. 9 units (3-0-6); second term. Prerequisite: APh/EE 9 ab or instructor's permission. The properties and photoelectrochemistry of semiconductors and semiconductor/liquid junction solar cells will be discussed. Topics include optical and electronic properties of semiconductors; electronic properties of semiconductor junctions with metals, liquids, and other semiconductors, in the dark and under illumination, with emphasis on semiconductor/liquid junctions in aqueous and nonaqueous media. Problems currently facing semiconductor/liquid junctions and practical applications of these systems will be highlighted. Instructor: Lewis (b), part a Not offered 2019–20.

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.) Not offered 2019–20.

Ch 144 ab. Advanced Organic Chemistry. 9 units (3-0-6); first term. *Prerequisites:* Ch 41 abc; Ch 21 abc recommended. An advanced survey of selected topics in modern organic chemistry. Topics vary from year to year and may include structural and theoretical organic chemistry; materials chemistry; macromolecular chemistry; mechanochemistry; molecular recognition/supramolecular chemistry; reaction mechanisms; reactive intermediates; pericyclic reactions; and photochemistry. Not offered 2019–20.

Ch 145. Chemical Biology of Proteins. 9 units (3-0-6); first term. *Prerequisites:* Ch 41 abc; Bi/Ch 110 recommended. An advanced survey of current and classic topics in chemical biology. Content draws largely from current literature and varies from year-to-year. Topics may include the structure, function, and synthesis of peptides and proteins; enzyme catalysis and inhibition; cellular metabolism; chemical genetics; proteomics; posttranslational modifications; chemical tools to study cellular dynamics; and enzyme evolution. Instructor: Ondrus.

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 and RNA by peptide analogs, proteins, and oligonucleotide-directed triple helical formation; RNA structure and RNA as catalysts (ribozymes). Not offered 2019–20.

Ch/ChE 147. Polymer Chemistry. 9 units (3-0-6), first 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: Robb.

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 first three weeks of the term. Graded pass/fail. Instructors: Fu, Stoltz, Ondrus.

Ch 153 abc. Advanced Inorganic Chemistry. 9 units (3-0-6); second (Ch 153 a), third (Ch 153 c offered in 2019–20, alternating with Ch 153 b in subsequent years) 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 to the characterization of inorganic and bioinorganic species, with an emphasis on the practical application of Moessbauer, EPR, and pulse EPR spectroscopies. Ch 153 c: Theoretical and spectroscopic approaches to understanding the electronic structure of transition metal ions. Topics in the 153bc alternate sequence may include saturation magnetization and zero-field splitting in magnetic circular dichroism and molecular magnetism, hyperfine interactions in electron paramagnetic resonance spectroscopy, Moessbauer and magnetic Moessbauer spectroscopy, vibronic interactions in electronic absorption and resonance Raman spectroscopy, and bonding analyses using x-ray absorption and/or emission spectroscopies. Instructors: Gray, Winkler (a), Hadt/Peters (c).

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, Agapie (a), part b Not offered 2019–20.

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.

BMB/Bi/Ch 170. Biochemistry and Biophysics of Macromolecules and Molecular Assemblies. 9 units (3-0-6). 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 term*. For course description, see Biochemistry and Molecular Biophysics.

BMB/Bi/Ch 174. Advanced Topics in Biochemistry. 6 units (3-0-3). For course description, see Biochemistry and Molecular Biophysics.

ESE/Ch 175. Physical Chemistry of Engineered Waters. 9 units (3-0-6). For course description, see Environmental Science and Engineering.

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

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

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

BMB/Ch 202 abc. Biochemistry Seminar Course. 1 unit; *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. Not offered 2019–20.

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. Instructor: Gray.

Ch 225. Advanced Quantum Chemistry. 9 units (3-0-6); *second term. Prerequisites: Ch125ab or equivalent, or permission of instructor.*

tors. The electronic structure of atoms and molecules, the interactions of radiation fields and matter, scattering theory, and reaction rate theory Instructor: Chan/Miller.

Ch 226. Optical and Nonlinear Spectroscopy. 9 units (3-0-6); third term. *Prerequisites:* Ch125ab, or equivalent instruction in quantum mechanics. Quantum mechanical foundations of optical spectroscopy as applied to chemical and material systems. Topics include optical properties of materials, nonlinear and quantum optics, and multidimensional spectroscopy. Instructors: Blake, Cushing.

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

Ch 242 ab. Chemical Synthesis. 9 units (3-0-6); first, second terms. *Prerequisite:* Ch 41 abc. An integrated approach to synthetic problem solving featuring an extensive review of modern synthetic reactions with concurrent development of strategies for synthesis design. Part a will focus on the application of modern methods of stereocontrol in the construction of stereochemically complex acyclic systems. Part b will focus on strategies and reactions for the synthesis of cyclic systems. Instructors: Stoltz (a), Reisman, Virgil (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 2019–20.

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 2020 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: Stoltz, Reeves.

Ch 251. Advanced Topics in Chemical Biology. 9 units (3-0-6); second term. *Prerequisites:* or 146 or consent of the instructor. Advanced Topics in Chemical Biology. Hours and units to be arranged. Content will vary from year to year; topics are chosen according to the interests of students and staff. Not offered 2019–20.

Ch 252. Advanced Topics in Chemical Physics. *Hours and units to be arranged.* Content will vary from year to year; topics are chosen according to the interests of students and staff. Not offered 2019–20.

Ch/Bi 253. Advanced Topics in Biochemistry. *6 units (2-0-4); third term.* Hours and units to be arranged. Content will vary from year to year; topics are chosen according to the interests of students and staff. Not offered 2019–20.

Bi/BE/Ch/ChE/Ge 269. Integrative Projects in Microbial Science and Engineering. *6 units (3-0-3).* For course description, see Biology.

Ch 279. Rotations in Chemistry. *Variable units as arranged with the advising faculty member; first, second, third terms.* By arrangement with members of the faculty, properly qualified graduate students will have the opportunity to engage in a short-term research project culminating in a presentation to their peers enrolled in the course and participating laboratories. (Pass-Fail only).

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 2019–20.

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 (3-5-1); first, second terms. Prerequisites: 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 2019–20.

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. Not offered 2019–20.

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

AM/CE 151. Dynamics and Vibration. 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 2019–20.

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. Not offered 2019–20.

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 2019–20.

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. Not offered 2019–20.

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 ab. Computational Solid Mechanics. 9 units 3-5-1. 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 2019–20.

AM/CE/ME 252. Linear and Nonlinear Waves in Structured Media. 9 units (2-1-6). For course description, see Applied Mechanics.

Ae/AM/CE/ME/Ge 265 ab. Static and Dynamic Failure of Brittle Solids and Interfaces, from the Micro to the Mega. 9 units; (3-0-6). For course description, see Aerospace.

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: Siapas.

CNS/Psy/Bi 102 ab. Brains, Minds, and Society. 9 units (3-0-6); *second, third terms*. *Prerequisites: Bi/CNS/NB/Psy 150 and CNS/Bi/Ph/CS/IB 187, or instructor's permission.* Introduction to the computations made by the brain during economic and social decision making and their neural substrates. Part a: Reinforcement learning. Unconscious and conscious processing. Emotion. Behavioral economics. Goal-directed and habit learning. Facial processing in social neuroscience. Part b: History and mechanisms of reinforcement. Associative learning. Mentalizing and strategic thinking. Neural basis of prosociality. Exploration-exploitation trad-

eff. Functions of basal ganglia. Instructors: O'Doherty/Adolphs, Camerer.

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

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. Instructor: O'Doherty. Not offered 2019–20.

Psy/CNS 132. Computational Reinforcement-learning in Biological and Non-biological Systems. 9 units (3-0-6). For course description, see Psychology.

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

Bi/CNS/NB 152. Neural Circuits and Physiology of Appetite and Body Homeostasis. 6 units (2-0-4); *spring*. For course description, see Biology.

Bi/CNS/NB 154. Principles of Neuroscience. 9 units (3-0-6). For course description, see Biology.

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

CS/CNS/EE 156 ab. Learning Systems. 9 units (3-1-5). For course description, see Computer Science.

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

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

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

Pi/CNS/NB/Bi/Psy 161. Consciousness. 9 units (3-0-6). For course description, see Philosophy.

Bi/CNS/NB 162. Cellular and Systems Neuroscience Laboratory. 12 units (2-4-6). For course description, see Biology.

NB/Bi/CNS 163. The Biological Basis of Neural Disorders. 6 units (3-0-3); *second term*. For course description, see Neurobiology.

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

CS/CNS/EE/IDS 165. Foundations of Machine Learning and Statistical Inference. 12 units (3-3-6). For course description, see Computer Science.

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/Psy/NB 176. Cognition. 9 units (4-0-5); *third term*. The cornerstone of current progress in understanding the mind, the brain, and the relationship between the two is the study of human and animal cognition. This course will provide an in-depth survey and analysis of behavioral observations, theoretical accounts, computational models, patient data, electrophysiological studies, and brain-imaging results on mental capacities such as attention, memory, emotion, object representation, language, and cognitive development. Instructor: Shimojo. Given in alternate years; Not Offered 2019–20.

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 units (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. Instructors: Meister, Perona, Shimojo, Tsao. Given in alternate years; Offered 2019–20.

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. Not Offered 2019–20.

BE/CS/CNS/Bi 191 ab. Biomolecular Computation. 9 units (3-0-6). For course description, see Bioengineering.

Bi/CNS/NB 195. Mathematics in Biology. 9 units (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/Psy 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. Not Offered 2019–20.

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

CNS 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. Not Offered 2019–20.

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

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. Instructor: Andersen.

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

Psy/CNS 285. Topics in Social, Cognitive, and Decision Sciences. 3 units (3-0-0). For course description, see Psychology.

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 (3-5-1); 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 fundamental algorithms; algorithm design principles, in particular recursion and dynamic programming; 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 projects 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. Instructor: Blank.

CS 3. Introduction to Software Design. *9 units (1-6-2); third term. Prerequisites: CS 2 or equivalent.* CS 3 is a practical introduction to designing large programs in a low-level language. Heavy emphasis is placed on documentation, testing, and software architecture. Students will work in teams in two 5-week long projects. In the first half of the course, teams will focus on testing and extensibility. In the second half of the course, teams will use POSIX APIs, as well as their own code from the first five weeks, to develop a large software deliverable. Software engineering topics covered include code reviews, testing and testability, code readability, API design, refactoring, and documentation. Instructor: Blank.

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 6/106 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 students to research areas in CS through weekly overview talks by Caltech faculty and aimed at first-year undergraduates. More senior students may wish to take the course to gain an understanding of the scope of research in computer science. Graded pass/fail. Instructor: Low.

EE/CS 10 ab. Introduction to Digital Logic and Embedded Systems. 6 units (2-3-1). For course description, see Electrical Engineering.

CS 11. Computer Language Lab. 3 units (0-3-0); first, second, third terms. *Prerequisites:* 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. This course is available for undergraduate students only. Graduate students should register for CS 111. CS 11 may be repeated for credit of up to a total of nine units. Instructors: Blank, Pinkston, Vanier.

CS 19 ab. Introduction to Computer Science in Industry. 2 units (1-0-1); first, second terms. This course will introduce students to CS in industry through weekly overview talks by alums and engineers in industry. It is aimed at second-year undergraduates. Others may wish to take the course to gain an understanding of the scope

of computer science in industry. Additionally students will complete short weekly assignments aimed at preparing them for interactions with industry. This course is closed to first and second term freshman for credit. Graded pass/fail. Instructor: Ralph.

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); first term. *Prerequisites:* Familiarity with C equivalent to having taken the CS 11 C track or CS 3. 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: Blank.

CS 37. Algorithms in the Real World. 9 units (2-6-1); first term. *Prerequisites:* CS 2, CS 24, Ma 6 or permission from instructor. This course introduces algorithms in the context of their usage in the real world. The course covers compression, advanced data structures, numerical algorithms, cryptography, computer algebra, and parallelism. The goal of the course is for students to see how to use theoretical algorithms in real-world contexts, focusing both on correctness and the nitty-gritty details and optimizations. Implementations focus on two orthogonal avenues: speed (for which C is used) and algorithmic thinking (for which Python is used). Not offered 2019–20.

CS 38. Algorithms. 9 units (3-0-6); third term. *Prerequisites:* CS 2; Ma/CS 6 a or Ma 121 a; and CS 21. 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.

CS 42. Computer Science Education in K-14 Settings. 6 units (2-2-2); first, second, third terms. This course will focus on computer science education in K-14 settings. Students will gain an understanding of the current state of computer science education within the United States, develop curricula targeted at students

from diverse backgrounds, and gain hands on teaching experience. Through readings from educational psychology and neuropsychology, students will become familiar with various pedagogical methods and theories of learning, while applying these in practice as part of a teaching group partnered with a local school or community college. Each week students are expected to spend about 2 hours teaching, 2 hours developing curricula, and 2 hours on readings and individual exercises. Pass/Fail only. May not be repeated. Instructor: Ralph.

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

CS/EE/ME 75 abc. 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 and third terms; units according to project selected. 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. Instructor: Burdick.

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: Faculty.

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: Faculty.

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: Faculty.

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.

HPS/PI/CS 110. Causation and Explanation. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

CS 111. Graduate Programming Practicum. *3 units (0-3-0); first, second, third terms. Prerequisites: CS 1 or equivalent.* 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. This course is available for graduate students only. Undergraduates should register for CS 11. Instructors: Blank, Pinkston, Vanier.

Ec/ACM/CS 112. Bayesian Statistics. *9 units (3-0-6).* For course description, see Economics.

CS 115. Functional Programming. *9 units (3-4-2); third term. Prerequisites: CS 1 and CS 4.* This course is a 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 language-

es. 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: Joshi.

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

CS 118. Logic Model Checking for Formal Software Verification. 9 units (3-3-3); *second term.* An introduction to the theory and practice of logic model checking as an aid in the formal proofs of correctness of concurrent programs and system designs. The specific focus is on automata-theoretic verification. The course includes a study of the theory underlying formal verification, the correctness of programs, and the use of software tools in designs. Not offered 2019–20.

EE/CS 119 abc. Advanced Digital Systems Design. 9 units (3-3-3). For course description, see Electrical Engineering.

CS/Ph 120. Quantum Cryptography. 9 units (3-0-6); *first term. Prerequisites: Ma 1b, Ph 2b or Ph 12b, CS 21, CS 38 or equivalent recommended (or instructor's permission).* This course is an introduction to quantum cryptography: how to use quantum effects, such as quantum entanglement and uncertainty, to implement cryptographic tasks with levels of security that are impossible to achieve classically. The course covers the fundamental ideas of quantum information that form the basis for quantum cryptography, such as entanglement and quantifying quantum knowledge. We will introduce the security definition for quantum key distribution and see protocols and proofs of security for this task. We will also discuss the basics of device-independent quantum cryptography as well as other cryptographic tasks and protocols, such as bit commitment or position-based cryptography. Instructor: Vidick.

CS/IDS 121. 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: Murray.

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

Prerequisites: CS 2, CS 38, CS/IDS 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 2019–20.

CS 123. Projects in Database Systems. 9 units (0-0-9); third term.

Prerequisites: CS/IDS 121 and CS 122. Students are expected to execute a substantial project in databases, write up a report describing their work, and make a presentation. Not offered 2019–20.

CS 124. Operating Systems. 12 units (3-6-3); third 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/CS/MedE 125. Digital Electronics and Design with FPGAs and VHDL. 9 units (3-6-0). For course description, see Electrical Engineering.

EE/Ma/CS 126 ab. Information Theory. 9 units (3-0-6); first, second terms. Prerequisites: Ma 3. For course description, see Electrical Engineering.

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

ME/CS/EE 129. Experimental Robotics. 9 units (3-6-0). For course description, see Mechanical Engineering.

CS 131. Programming Languages. 9 units (3-0-6); third term. Prerequisites: CS 4. CS 131 is a course on programming languages and their implementation. It teaches students how to program in a number of simplified languages representing the major programming paradigms in use today (imperative, object-oriented, and functional). It will also teach students how to build and modify the implementations of these languages. Emphasis will not be on syntax or parsing but on the essential differences in these languages and their implementations. Both dynamically-typed and statically-typed languages will be implemented. Relevant theory will be covered as needed. Implementations will mostly be interpreters, but some features of compilers will be covered if time permits. Enrollment limited to 20 students. Instructor: Vanier.

ME/CS/EE 133 abc. Robotics. 9 units (3-3-3). For course description, see Mechanical Engineering.

ME/CS/EE 134. Robotic Systems. 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.

EE/Ma/CS/IDS 136. Topics in Information Theory. 9 units (3-0-6). For course description, see Electrical Engineering.

CS 138. Computer Algorithms. 9 units (3-0-6); third term. This course is identical to CS 38. Only graduate students for whom this is the first algorithms course are allowed to register for CS 138. See the CS 38 entry for prerequisites and course description. Instructor: Schulman.

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

CS 141. Hack Society: Projects from the Public Sector. 9 units (0-0-9); second term. Prerequisites: CS/IDS 142, 143, CMS/CS/EE/IDS 144, or permission from instructor. There is a large gap between

the public and private sectors' effective use of technology. This gap presents an opportunity for the development of innovative solutions to problems faced by society. Students will develop technology-based projects that address this gap. Course material will offer an introduction to the design, development, and analysis of digital technology with examples derived from services typically found in the public sector. Not offered 2019–20.

CS/IDS 142. Distributed Computing. 9 units (3-2-4); first 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. Instructors: Murray, Chandy.

CS/EE/IDS 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 focuses on the link layer (two) through the transport layer (four) of Internet protocols. It has two distinct components, analytical and systems. In the analytical part, after a quick summary of basic mechanisms on the Internet, we will focus on congestion control and explain: (1) How to model congestion control algorithms? (2) Is the model well defined? (3) How to characterize the equilibrium points of the model? (4) How to prove the stability of the equilibrium points? We will study basic results in ordinary differential equations, convex optimization, Lyapunov stability theorems, passivity theorems, gradient descent, contraction mapping, and Nyquist stability theory. We will apply these results to prove equilibrium and stability properties of the congestion control models and explore their practical implications. In the systems part, the students will build a software simulator of Internet routing and congestion control algorithms. The goal is not only to expose students to basic analytical tools that are applicable beyond congestion control, but also to demonstrate in depth the entire process of understanding a physical system, building mathematical models of the system, analyzing the models, exploring the practical implications of the analysis, and using the insights to improve the design. Not offered 2019–20.

CMS/CS/EE/IDS 144. Networks: Structure & Economics. 12 units (3-4-5). 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/IDS 144 or CS/IDS 142 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. Control and Optimization of Networks. 9 units (3-3-3); first term. *Prerequisites:* Ma 2, Ma 3 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 in the design, analysis, control, and optimization of networks. Usually offered in odd years. Offered 2019–20. Instructor: Low.

EE/CS 147. Digital Ventures Design. 9 units (3-3-3); first term. *Prerequisites:* none. For course description, see Electrical Engineering.

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

CS/SS/EC 149. Algorithmic Economics. 9 units (3-0-6); second term. This course will equip students to engage with active research at the intersection of social and information sciences, including: algorithmic game theory and mechanism design; auctions; matching markets; and learning in games. Not offered 2019–20.

CS/IDS 150 ab. Probability and Algorithms. 9 units (3-0-6); first term. *Prerequisites:* part a: CS 38 and Ma 5 abc; part b: part a or another introductory course in discrete probability. Part a: The probabilistic method and randomized algorithms. Deviation bounds, k -wise independence, graph problems, identity testing, derandomization and parallelization, metric space embeddings, local lemma. Part b: Further topics such as weighted sampling, epsilon-biased sample spaces, advanced deviation inequalities, rapidly mixing Markov chains, analysis of boolean functions, expander graphs, and other gems in the design and analysis of probabilistic algorithms. Parts a & b are offered in alternate years. Part b will be offered in 2019–20. Instructor: Schulman.

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 2019–20.

CS 152. Introduction to Cryptography. 12 units (3-0-9); first term. *Prerequisites:* Ma 1b, CS 21, CS 38 or equivalent recommended. This course is an introduction to the foundations of cryptography.

The first part of the course introduces fundamental constructions in private-key cryptography, including one-way functions, pseudo-random generators and authentication, and in public-key cryptography, including trapdoor one-way functions, collision-resistant hash functions and digital signatures. The second part of the course covers selected topics such as interactive protocols and zero knowledge, the learning with errors problem and homomorphic encryption, and quantum cryptography: quantum money, quantum key distribution. The course is mostly theoretical and requires mathematical maturity. There will be a small programming component. Not offered 2019–20.

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

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

CS/CNS/EE 156 ab. Learning Systems. 9 units (3-1-5); 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. Instructor: Abu-Mostafa.

IDS/ACM/CS 157. Statistical Inference. 9 units (3-2-4). For course description, see Information and Data Sciences.

IDS/ACM/CS 158. Fundamentals of Statistical Learning. 9 units (3-3-3). For course description, see Information and Data Sciences.

CS/CNS/EE/IDS 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. Not offered 2019–20.

EE/CS/IDS 160. Fundamentals of Information Transmission and Storage. 9 units (3-0-6). For course description, see Electrical Engineering.

EE/CS 161. Big Data Networks. 9 units (3-0-6); third term. For course description, see Electrical Engineering.

CS/IDS 162. Data, Algorithms and Society. 9 units (3-0-6); third term. *Prerequisites:* CS 38 and CS 155 or 156a. This course examines algorithms and data practices in fields such as machine learning, privacy, and communication networks through a social lens. We will draw upon theory and practices from art, media, computer science and technology studies to critically analyze algorithms and their implementations within society. The course includes projects, lectures, readings, and discussions. Students will learn mathematical formalisms, critical thinking and creative problem solving to connect algorithms to their practical implementations within social, cultural, economic, legal and political contexts. Enrollment by application. Taught concurrently with VC 72 and can only be taken once, as VC 72 or CS/IDS 162. Instructor: Mushkin/Ralph.

CS/CNS/EE/IDS 165. Foundations of Machine Learning and Statistical Inference. 12 units (3-3-6); second term. *Prerequisites:* CMS/ACM/IDS 113, ACM/EE/IDS 116, CS 156a, ACM/CS/IDS 157 or instructor's permission. The course assumes students are comfortable with analysis, probability, statistics, and basic programming. This course will cover core concepts in machine learning and statistical inference. The ML concepts covered are spectral methods (matrices and tensors), non-convex optimization, probabilistic models, neural networks, representation theory, and generalization. In statistical inference, the topics covered are detection and estimation, sufficient statistics, Cramer-Rao bounds, Rao-Blackwell theory, variational inference, and multiple testing. In addition to covering the core concepts, the course encourages students to ask critical questions such as: How relevant is theory in the age of deep learning? What are the outstanding open problems? Assignments will include exploring failure modes of popular algorithms, in addition to traditional problem-solving type questions. Instructor: Anandkumar.

EE/CS/IDS 167. Introduction to Data Compression and Storage. 9 units (3-0-6). For course description, see Electrical Engineering.

CS/CNS 171. Computer Graphics Laboratory. 12 units (3-6-3); first term. *Prerequisites:* Extensive programming experience and proficiency in linear algebra, starting with CS2 and Ma1b. This is a challenging course that introduces the basic ideas behind computer graphics and some of its fundamental algorithms. Topics include graphics input and output, the graphics pipeline, sampling and im-

age manipulation, three-dimensional transformations and interactive modeling, basics of physically based modeling and animation, simple shading models and their hardware implementation, and some of the 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:* Extensive programming experience, CS/CNS 171 or instructor's permission. This laboratory class offers students an opportunity for independent work including 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 possible improvements to the basic methods. May be repeated for credit with instructor's permission. Instructor: Barr.

EE/CS/MedE 175. Digital Circuits Analysis and Design with Complete VHDL and RTL Approach. 9 units (3-6-0). For course description, see Electrical Engineering.

CS 176. Computer Graphics Research. 9 units (3-3-3); second term. *Prerequisites:* 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. Not offered 2019–20.

CS/ACM 177 ab. Discrete Differential Geometry: Theory and Applications. 9 units (3-3-3); second, third terms. Working knowledge of multivariate calculus and linear algebra as well as fluency in some implementation language is expected. Subject matter covered: differential geometry of curves and surfaces, classical exterior calculus, discrete exterior calculus, sampling and reconstruction of differential forms, low dimensional algebraic and computational topology, Morse theory, Noether's theorem, Helmholtz-Hodge decomposition, structure preserving time integration, connections and their curvatures on complex line bundles. Applications include elastica and rods, surface parameterization, conformal surface deformations, computation of geodesics, tangent vector field design, connections, discrete thin shells, fluids, electromagnetism, and elasticity. Instructor: Schröder.

CS/IDS 178. Numerical Algorithms and their Implementation. 9 units (3-3-3); second term. Prerequisites: CS 2. This course gives students the understanding necessary to choose and implement basic numerical algorithms as needed in everyday programming practice. Concepts include: sources of numerical error, stability, convergence, ill-conditioning, and efficiency. Algorithms covered include solution of linear systems (direct and iterative methods), orthogonalization, SVD, interpolation and approximation, numerical integration, solution of ODEs and PDEs, transform methods (Fourier, Wavelet), and low rank approximation such as multipole expansions. Not offered 2019–20.

CS 179. GPU Programming. 9 units (3-3-3); third term. Prerequisites: Good working knowledge of C/C++. Some experience with computer graphics algorithms preferred. 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 use nVidia's parallel computing architecture, CUDA. Labwork requires extensive programming. Instructor: Barr.

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

Bi/BE/CS 183. Introduction to Computational Biology and Bioinformatics. 9 units (3-0-6). For course description, see Biology.

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 (3-0-6). For course description, see Bioengineering.

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

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

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 2019–20.

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.

CS 287. Center for the Mathematics of Information Seminar. 3, 6, or 9 units, at the instructor's discretion; first, second, third terms. Instructor's permission required. Instructor: Staff.

COMPUTING AND MATHEMATICAL SCIENCES

CMS/ACM/IDS 107. Linear Analysis with Applications. 12 units (3-3-6); first term. *Prerequisites: ACM/IDS 104 or equivalent, Ma 1 b or equivalent.* Covers the basic algebraic, geometric, and topological properties of normed linear spaces, inner-product spaces, and linear maps. Emphasis is placed both on rigorous mathematical development and on applications to control theory, data analysis and partial differential equations. Instructor: Stuart.

CMS/ACM/IDS 113. Mathematical Optimization. 12 units (3-0-9); first term. *Prerequisites: ACM 11 and ACM 104, or instructor's permission.* 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. Instructor: Chandrasekaran.

CMS 117. Probability Theory and Stochastic Processes. 12 units (3-0-9); first term. *Prerequisites: ACM/IDS 104, ACM/EE/IDS 116*

or instructor's permission. This course offers a rigorous introduction to probability and stochastic processes. Emphasis is placed on the interaction between inequalities and limit theorems, as well as contemporary applications in computing and mathematical sciences. Topics include probability measures, random variables and expectation, independence, concentration inequalities, distances between probability measures, modes of convergence, laws of large numbers and central limit theorem, Gaussian and Poisson approximation, conditional expectation and conditional distributions, filtrations, and discrete-time martingales. Instructor: Tropp.

CMS/CS/IDS 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, and ACM/EE/IDS 116 or CMS/ACM/IDS 113 or equivalent. This course develops core principles for the analysis and design of algorithms. Basic material includes mathematical techniques for analyzing performance in terms of resources, such as time, space, and randomness. The course introduces the major paradigms for algorithm design, including greedy methods, divide-and-conquer, dynamic programming, linear and semidefinite programming, randomized algorithms, and online learning. Instructor: Vidick.

CMS/CS/EE/IDS 144. Networks: Structure & Economics. 12 units (3-4-5); second term. Prerequisites: Ma 2, Ma 3, Ma/CS 6 a, and CS 38, or instructor permission. Social networks, the web, and the internet are essential parts of our lives, and we depend on them every day. This course studies how they work and the “big” ideas behind our networked lives. Questions explored include: 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 expects students to be comfortable with graph theory, probability, and basic programming. Instructor: Wierman.

CMS/CS/CNS/EE/IDS 155. Machine Learning & Data Mining. 12 units (3-3-6); second term. Prerequisites: CS/CNS/EE 156 a. Having a sufficient background in algorithms, linear algebra, calculus, probability, and statistics, is highly recommended. 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. The course will focus on basic foundational concepts underpinning and motivating modern machine learning and data mining approaches. We will also discuss recent research developments. Instructor: Yue.

CMS 270. Advanced Topics in Computing and Mathematical Sciences. *Units by arrangement; second term.* Advanced topics that will vary according to student and instructor interest. May be repeated for credit. Instructor: Murray.

CMS 290 abc. Computing and Mathematical Sciences Colloquium. *1 unit; first, second, third terms. Registration is limited to graduate students in the CMS department only.* This course is a research seminar course covering topics at the intersection of mathematics, computation, and their applications. Students are asked to attend one seminar per week (from any seminar series on campus) on topics related to computing and mathematical sciences. This course is a requirement for first-year PhD students in the CMS department. Instructor: Schröder.

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 or CDS 112 (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: Staff.

CDS 110. Introduction to Feedback Control Systems. *9 units (3-3-3); third 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. Instructor: Seinfeld.

CDS 112. Optimal Control and Estimation. *9 units (3-0-6); second term. Prerequisites: CDS 110 (or equivalent) and CDS 131.* Optimi-

zation-based design of control systems, including optimal control and receding horizon control. Introductory random processes and optimal estimation. Kalman filtering and nonlinear filtering methods for autonomous systems. Instructor: Chung.

CDS 131. Linear Systems Theory. 9 units (3-0-6); first term.

Prerequisites: Ma 1b, Ma 2, ACM/IDS 104 or equivalent (may be taken concurrently). Basic system concepts; state-space and I/O representation. Properties of linear systems, including stability, performance, robustness. Reachability, observability, minimality, state and output-feedback. Instructor: Murray.

CDS 141. Network Control Systems. 9 units (3-2-4); third term.

Variety of case studies and projects from control, communication and computing in complex tech, bio, neuro, eco, and socioeconomic networks, particularly smartgrid, internet, sensorimotor control, cell biology, medical physiology, and human and animal social organization. Emphasis on leveraging universal laws and architectures but adding domain specific details. Can be taken after CDS 231 (to see applications of the theory) or before (to motivate the theory). Not offered 2019–20.

CDS 190. Independent Work in Control and Dynamical Systems.

Units to be arranged; first, second, third terms; maximum two terms. Prerequisite: CDS 110. Research project in control and dynamical systems, supervised by a CDS faculty member.

CDS 231. Robust Control Theory. 9 units (3-2-4); second term.

Prerequisites: CMS/ACM/IDS 107, CMS/ACM/IDS 113, and CDS 131 (or equivalents). Linear input/output models (multi-state difference and differential equations). Stability, input/output norms. Uncertainty, including noise, disturbances, parametric uncertainty, unmodeled dynamics, and structured uncertainty (LTI/LTV). Tradeoffs, robustness versus efficiency, conservation laws and hard limits in time and frequency domain. Synthesis of robust control systems. Co-design of sparse and limited (delayed, quantized, saturating, noisy) sensing, communications, computing, and actuation. Layering, localization, and distributed control. Interplay between automation, optimization, control, modeling and system identification, and machine learning. Computational scalability exploiting sparsity and structure, nonlinear dynamics and sum of squares, global stability, regions of attraction. Motivation throughout from case studies from tech, neuro, bio, and socioeconomic networks, explored in more detail in CDS 141. Not offered 2019–20.

CDS 232. Nonlinear Dynamics. 9 units (3-0-6); second term. *Pre-*

requisites: CMS/ACM/IDS 107 and CDS 231. This course studies nonlinear dynamical systems beginning from first principles. Topics include: existence and uniqueness properties of solutions to non-

linear ODEs, stability of nonlinear systems from the perspective of Lyapunov, and behavior unique to nonlinear systems; for example: stability of periodic orbits, Poincaré maps and stability/invariance of sets. The dynamics of robotic systems will be used as a motivating example. Instructor: Ames.

CDS 233. Nonlinear Control. 9 units (3-0-6); third term. Prerequisites: CDS 231 and CDS 232. This course studies nonlinear control systems from Lyapunov perspective. Beginning with feedback linearization and the stabilization of feedback linearizable system, these concepts are related to control Lyapunov functions, and corresponding stabilization results in the context of optimization based controllers. Advanced topics that build upon these core results will be discussed including: stability of periodic orbits, controller synthesis through virtual constraints, safety-critical controllers, and the role of physical constraints and actuator limits. The control of robotic systems will be used as a motivating example. Instructor: Ames.

CDS 242. Hybrid Systems: Dynamics and Control. 9 units (3-2-4); third term. Prerequisites: CDS 231 and CDS 232. This class studies hybrid dynamical systems: systems that display both discrete and continuous dynamics. This includes topics on dynamic properties unique to hybrid system: stability types, hybrid periodic orbits, Zeno equilibria and behavior. Additionally, the nonlinear control of these systems will be considered in the context of feedback linearization and control Lyapunov functions. Applications to mechanical systems undergoing impacts will be considered, with a special emphasis on bipedal robotic walking. Not offered 2019–20.

CDS 243. Adaptive Control. 4 units (2-0-2); third term. Prerequisites: CDS 231 AND CDS 232. Specification and design of control systems that operate in the presence of uncertainties and unforeseen events. Robust and optimal linear control methods, including LQR, LQG and LTR control. Design and analysis of model reference adaptive control (MRAC) for nonlinear uncertain dynamical systems with extensions to output feedback. Offered in alternate years. Instructor: Lavretsky.

CDS 244. System Identification. 4 units (2-0-2); third term. Prerequisites: CDS 231 and CDS 232. Mathematical treatment of system identification methods for dynamical systems, with applications. Nonlinear dynamics and models for parameter identification. Gradient and least-squares estimators and variants. System identification with adaptive predictors and state observers. Parameter estimation in the presence of non-parametric uncertainties. Introduction to adaptive control. Offered in alternate years. Not offered 2019–20.

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: Faculty.

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.

BEM/Ec/PS 80. Frontiers in Social Sciences. 1 unit (1-0-0). For course description, see Business, Economics and Management.

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. Firms, Competition, and 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. Instructor: Shum.

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/ACM/CS 112. Bayesian Statistics. 9 units (3-0-6); second term. *Prerequisites:* Ma 3, ACM/EE/IDS 116 or equivalent. This course provides an introduction to Bayesian Statistics and its applications to data analysis in various fields. Topics include: discrete models, regression models, hierarchical models, model comparison, and MCMC methods. The course combines an introduction to basic theory with a hands-on emphasis on learning how to use these methods in practice so that students can apply them in their own work. Previous familiarity with frequentist statistics is useful but not required. Instructor: Rangel.

Ec 117. Matching Markets. 9 units (3-0-6); third term. We will tackle the fundamental question of how to allocate resources and organize exchange in the absence of prices. Examples includes finding a partner, allocating students to schools, and matching donors to patients in the context of organ transplantations. While the main focus will be on formal models, we will also reason about the practical implications of the theory. Instructor: Pomatto.

BEM/Ec/ESE 119. Environmental Economics. 9 units (3-0-6). For course description, see Business, Economics, and Management.

Ec 121 ab. Theory of Value. 9 units (3-0-6); first, third terms. *Prerequisites:* Ec 11 and Ma 1b (may be taken concurrently). A study of consumer preference, the structure and conduct of markets, factor pricing, measures of economic efficiency, and the interdependence of markets in reaching a general equilibrium. Instructors: Border, Schenone.

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

Ec 123. Econometric Analysis of Discrete Choice. 9 units (3-0-6); second term. Prerequisites: Ec 122. This course uses advanced econometric tools to analyze why people make the choices that they do in many domains- whether to make investments in peer-to-peer lending, consumer shopping between brands, where to go to college (Caltech or MIT?), choosing between modes of transportation (car, metro, Uber/Lyft, or bicycle), etc. We will focus on applications of discrete choice models (in which the dependent variable to be explained is usually a 0-1, Yes or No choice). The statistical models create estimates of behavioral parameters which describe numerically how much people value different goods or outcomes and how random their responses are. Models studied include logit, nested logit, probit, and mixed logit etc. Simulation techniques that allow estimation of otherwise intractable models will also be discussed. Models of this kind are routinely used in business and government, but are often misused and misinterpreted unless they are deeply understood. Instructor: Xin.

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. Not offered 2019–20.

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 2019–20.

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. Not offered 2019–20.

Ec 131. Market Design. 9 units (3-0-6); first term. Prerequisites: Ec 11, Ec 121, and PS/Ec 172. The class studies different mechanisms to allocate a scarce resource, frequently called markets, using theoretical models. We will cover centralized markets, which clear via a single price, waiting or rationing, or use centralized algorithms to allocate demand and supply; decentralized markets, which clear via search; and auction markets. In each case, we will study how market rules determine the incentives of market participant and how to design these markets, focusing on efficiency and revenue maximization. Applications to electricity markets, concert tickets, ride-sharing, labor markets, school choice, dating markets, sponsored search ad auctions, and spectrum auctions will be covered. Instructor: Doval.

Ec 135. Economics of Uncertainty and Information. 9 units (3-0-6); first term. Prerequisite: Ec 11. 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 136. Behavioral Decision Theory. 9 units (3-0-6); second term. Prerequisites: Ma 3. Ec 121 is recommended as background, but is not a prerequisite. This course is an intermediate-level class on individual-level theory. The method used posits precise assumptions about general behavior (axioms) then finds equivalent ways to model them in mathematically convenient terms. We will cover both the traditional “rational” approach, and more recent “behavioral” models that incorporate psychological principles, in domains of intertemporal choice, random (stochastic) choice, menu choice, and revealed preferences. Students are expected to understand rigorous mathematical proofs. The class also includes serious discussion of the value of experimental evidence motivating new theories. Instructors: Saito.

Ec 140. Economic Progress. 9 units (3-0-6); third term. Prerequisites: Ec 11; 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. Instructors: Hoffman.

CS/SS/Ec 149. Algorithmic Economics. 9 units (3-0-6). For course description, see Computer Science.

BEM/Ec 150. Business Analytics. 9 units (3-0-6). *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 ab. Convex Analysis and Economic Theory. 9 units (3-0-6); *first, second terms.* *Prerequisites:* Ma 1. Ec 121a is recommended. Introduction to the use of convex analysis in economic theory. Includes separating hyperplane theorems, continuity and differentiability properties of convex and concave functions, support functions, subdifferentials, Fenchel conjugates, saddlepoint theorem, theorems of the alternative, polyhedra, linear programming, and duality in graphs. Introduction to discrete convex analysis and matroids. Emphasis is on the finite-dimensional case, but infinite-dimensional spaces will be discussed. Applications to core convergence, cost and production functions, mathematical finance, decision theory, incentive design, and game theory. Instructor: Border.

ELECTRICAL ENGINEERING

EE 1. The Science of Data, Signals, and Information. 9 units (3-0-6); *third term.* Electrical Engineering has given rise to many key developments at the interface between the physical world and the information world. Fundamental ideas in data acquisition, sampling, signal representation, and quantification of information have their origin in electrical engineering. This course introduces these ideas and discusses signal representations, the interplay between time and frequency domains, difference equations and filtering, noise and denoising, data transmission over channels with limited capacity, signal quantization, feedback and neural networks, and how humans interpret data and information. Applications in various areas

of science and engineering are covered. Satisfies the menu requirement of the Caltech core curriculum. Instructor: Vaidyanathan.

EE 2. Electrical Engineering Entrepreneurial and Research Seminar. *1 unit; second term. Required for EE undergraduates.* Weekly seminar given by successful entrepreneurs and EE faculty, broadly describing their path to success and introducing different areas of research in 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, specifically, research going on at Caltech and in the industry. Instructor: Emami.

EE/ME 7. Introduction to Mechatronics. *6 units (2-3-1); first 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/CS 10 ab. Introduction to Digital Logic and Embedded Systems. *6 units (2-3-1); second, third terms.* 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. The course will cover basic digital logic, programmable logic devices, CPU and embedded system architecture, and embedded systems programming principles (interfacing to hardware, events, user interfaces, and multi-tasking). Instructor: George.

EE 13. Electronic System Prototyping. *3 units (0-3-0); first term.* This course is intended to introduce the student to the technologies and techniques used to fabricate electronic systems. The course will cover the skills needed to use standard CAD tools for circuit prototyping. This includes schematic capture and printed circuit board design. Additionally, soldering techniques will be covered for circuit fabrication as well as some basic debugging skills. Each student will construct a system from schematic to PCB to soldering the final prototype. Instructor: George.

APh/EE 23. Demonstration Lectures in Classical and Quantum Photonics. 9 units (3-0-6). For course description, see Applied Physics.

APh/EE 24. Introductory Optics and Photonics Laboratory. 9 units (1-3-5). For course description, see Applied Physics.

EE 40. Physics of Electrical Engineering. 9 units (3-0-6); *third term*. This course provides an introduction to the fundamental physics of modern device technologies in electrical engineering used for sensing, communications, computing, imaging, and displays. The course overviews topics including semiconductor physics, quantum mechanics, electromagnetics, and optics with emphasis on physical operation principles of devices. Example technologies include integrated circuits, optical and wireless communications, micromechanical systems, lasers, high-resolution displays, LED lighting, and imaging. Instructor: Marandi.

EE 44. Deterministic Analysis of Systems and Circuits. 12 units (4-0-8); *first term*. *Prerequisites:* Ph 1 abc, can be taken concurrently with Ma 2 and Ph 2 a. Modeling of physical systems by conversion to mathematical abstractions with an emphasis on electrical systems. Introduction to deterministic methods of system analysis, including matrix representations, time-domain analysis using impulse and step responses, signal superposition and convolution, Heaviside operator solutions to systems of linear differential equations, transfer functions, Laplace and Fourier transforms. The course emphasizes examples from the electrical circuits (e.g., energy and data converters, wired and wireless communication channels, instrumentation, and sensing) , while providing some exposure to other selected applications of the deterministic analysis tool (e.g., public opinion, acoustic cancellation, financial markets, traffic, drug delivery, mechanical systems, news cycles, and heat exchange). Instructor: Hajimiri.

EE 45. Electronics Systems and 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 53. Microprocessor Project Laboratory. 12 units (0-12-0); *first, second, third terms*. *Prerequisites:* EE/CS 10 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. Not offered 2019–20. Instructor: George.

CS/EE/ME 75 abc. 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 and third terms; 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: Staff.

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: Ohanian.

EE 91 ab. Experimental Projects in Electronic Circuits. 9 units (1-8-0); first, second terms. *Prerequisites: EE 45. Recommended: EE/CS 10 ab, and EE/MedE 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. Instructor: Ohanian.

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: Emami.

ACM/EE 106 ab. Introductory Methods of Computational Mathematics. 12 units (3-0-9); For course description, see Applied and Computational Mathematics.

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

EE 110 abc. Embedded Systems Design Laboratory. 9 units (3-4-2); first, second, third terms. The student will design, build, and program a specified microprocessor-based embedded system. This structured laboratory is organized to familiarize the student with large-scale digital and embedded system design, electronic circuit construction techniques, modern development facilities, and embedded systems programming. The lectures cover topics in embedded system design such as display technologies, interfacing to analog signals, communication protocols, PCB design, and programming in high-level and assembly languages. Given in alternate years; Offered 2019–20. Instructor: George.

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. Instructor: Vaidyanathan.

EE 112. Introduction to Signal Processing from Data. 9 units (3-0-6); second term. *Prerequisites:* EE 111 or equivalent. Math 3 recommended. Fundamentals of digital signal processing, extracting information from data by linear filtering, recursive and non-recursive filters, structural and flow graph representations for filters, data-adaptive filtering, multirate sampling, efficient data representations with filter banks, Nyquist and sub-Nyquist sampling, sensor array signal processing, estimating direction of arrival (DOA) information from noisy data, and spectrum estimation. 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. Instructor: 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. Not offered 2019–20. Instructor: Hajimiri.

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 2019–20.

ACM/EE/IDS 116. Introduction to Probability Models. 9 units (3-1-5). For course description, see Applied and Computational Mathematics.

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

EE/CS 119 abc. Advanced Digital Systems Design. 9 units (3-3-3); first, second term; 9 units (1-8-0) third term. Prerequisites: EE/CS 10 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 tech-

nologies and tools. Given in alternate years; not offered 2019–20.
Instructor: George.

EE 121. Computational Signal Processing. (3-0-9); *first. Prerequisites: EE 111, ACM/EE/IDS 116, ACM/IDS 104.* The role of computation in the acquisition, representation, and processing of signals. The course develops methodology based on linear algebra and optimization, with an emphasis on the interplay between structure, algorithms, and accuracy in the design and analysis of the methods. Specific topics covered include deterministic and stochastic signal models, statistical signal processing, inverse problems, and regularization. Problems arising in contemporary applications in the sciences and engineering are discussed, although the focus is on the common abstractions and methodological frameworks that are employed in the solution of these problems. Not offered 2019–20.
Instructor: Chandrasekaran.

EE/MedE 124. Mixed-mode Integrated Circuits. 9 units (3-0-6); *third 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. Instructor: Emami

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

EE/Ma/CS 126 ab. Information Theory. 9 units (3-0-6); *first, second terms. Prerequisites: Ma 3.* 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, Markov, ergodic, and Gaussian. Calculation of capacity and rate-distortion functions. Universal source codes. Side infor-

mation 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/IDS 127, EE/CS 161, and EE/CS/IDS 167, should prepare the student for research in information theory, coding theory, wireless communications, and/or data compression. Instructor: Effros.

EE/Ma/CS/IDS 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. The students will become acquainted with encoding and decoding algorithms, design principles and performance evaluation of codes. Instructor: Kostina.

EE 128 ab. Selected Topics in Digital Signal Processing. 9 units (3-0-6); second, third terms. *Prerequisites:* EE 111 and EE/CS/IDS 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 2019–20.

ME/CS/EE 129. Experimental Robotics. 9 units (3-6-0). For course description, see Mechanical Engineering.

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. Not offered 2019–20. Instructor: Yariv.

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

ME/CS/EE 133 abc. Robotics. 9 units (3-3-3). For course description, see Mechanical Engineering.

ME/CS/EE 134. Robotic Systems. 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. Prerequisites: EE 44, Ma 2, or equivalent. Basic power system analysis: phasor representation, 3-phase transmission system, transmission line models, transformer models, per-unit analysis, network matrix, power flow equations, power flow algorithms, optimal powerflow (OPF) problems, swing dynamics and stability. Current research topics such as (may vary each year): convex relaxation of OPF, frequency regulation, energy functions and contraction regions, volt/var control, storage optimization, electric vehicles charging, demand response. Instructor: Low.

EE/Ma/CS/IDS 136. Topics in Information Theory. 9 units (3-0-6); third term. Prerequisites: undergraduate calculus and probability. 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. Not Offered 2019–20. Instructor: Kostina.

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

CMS/CS/EE/IDS 144. Networks: Structure & Economics. 12 units (3-4-5). 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. Control and Optimization of Networks. 9 units (3-3-3). For course description, see Computer Science.

EE/CS 147. Digital Ventures Design. 9 units (3-3-3); first term. Prerequisites: none. This course aims to offer the scientific foundations of analysis, design, development, and launching of innovative

digital products and study elements of their success and failure. The course provides students with an opportunity to experience combined team-based design, engineering, and entrepreneurship. The lectures present a disciplined step-by-step approach to develop new ventures based on technological innovation in this space, and with invited speakers, cover topics such as market analysis, user/product interaction and design, core competency and competitive position, customer acquisition, business model design, unit economics and viability, and product planning. Throughout the term students will work within an interdisciplinary team of their peers to conceive an innovative digital product concept and produce a business plan and a working prototype. The course project culminates in a public presentation and a final report. Every year the course and projects focus on a particular emerging technology theme. Not offered 2019–20. Instructor: Staff.

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. Instructor: Perona.

EE/APh 149. Frontiers of Nonlinear Photonics. 9 units (3-0-6); second term. This course overviews recent advances in photonics with emphasis on devices and systems that utilize nonlinearities. A wide range of nonlinearities in the classical and quantum regimes is covered, including but not limited to second- and third-order nonlinear susceptibilities, Kerr, Raman, optomechanical, thermal, and multi-photon nonlinearities. A wide range of photonic platforms is also considered ranging from bulk to ultrafast and integrated photonics. The course includes an overview of the concepts as well as review and discussion of recent literature and advances in the field. Instructor: Marandi.

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 152. High Frequency Systems Laboratory. 12 units (2-3-7); first term. Prerequisites: EE 45 or equivalent. EE 153 recommended. The student will develop a strong, working knowledge of high-frequency systems covering RF and microwave frequencies. The essential building blocks of these systems will be studied along with the fundamental system concepts employed in their use. The first part of the course will focus on the design and measurement of core system building blocks; such as filters, amplifiers, mixers, and oscillators. Lectures will introduce key concepts followed by weekly laboratory sessions where the student will design and characterize these various system components. During the second part of the course, the student will develop their own high-frequency system, focused on a topic within remote sensing, communications, radar, or one within their own field of research. Instructor: Russell.

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.

EE 154 ab. Practical Electronics for Space Applications. 9 units (2-3-4); second and third terms. Part a: Subsystem Design: Students will be exposed to design for subsystem electronics in the space environment, including an understanding of the space environment, common approaches for low cost spacecraft, atmospheric / analogue testing, and discussions of risk. Emphasis on a practical exposure to early subsystem design for a TRL 3-4 effort. Part b: Subsystems to System Interfacing: Builds upon the first term by extending subsystems to be compatible with “spacecraft”, including a near-space “flight” of prototype subsystems on a high-altitude balloon flight. Focus on qualification for the flight environment appropriate to a TRL 4-5 effort. Not Offered 2019-20. Instructor: Klesh.

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

CS/CNS/EE 156 ab. Learning Systems. 9 units (3-1-5). 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/IDS 159. Advanced Topics in Machine Learning. 9 units (3-0-6). For course description, see Computer Science.

EE/CS/IDS 160. Fundamentals of Information Transmission and Storage. 9 units (3-0-6); *second term*. Basics of information theory: entropy, mutual information, source and channel coding theorems. Basics of coding theory: error-correcting codes for information transmission and storage, block codes, algebraic codes, sparse graph codes. Basics of digital communications: sampling, quantization, digital modulation, matched filters, equalization. Instructor: Kostina.

EE/CS 161. Big Data Networks. 9 units (3-0-6); *third term*. *Prerequisites: Linear Algebra ACM/IDS 104 and Probability and Random Processes ACM/EE/IDS 116 or their equivalents.* Next generation networks will have tens of billions of nodes forming cyber-physical systems and the Internet of Things. A number of fundamental scientific and technological challenges must be overcome to deliver on this vision. This course will focus on (1) How to boost efficiency and reliability in large networks; the role of network coding, distributed storage, and distributed caching; (2) How to manage wireless access on a massive scale; modern random access and topology formation techniques; and (3) New vistas in big data networks, including distributed computing over networks and crowdsourcing. A selected subset of these problems, their mathematical underpinnings, state-of-the-art solutions, and challenges ahead will be covered. Given in alternate years. Not offered 2019–20. Instructor: Hassibi.

EE 163. Communication Theory. 9 units (3-0-6); *second term*. *Prerequisites: EE 111; ACM/EE/IDS 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. Capacity measures; multiple antenna and multiple carrier communication systems; wireless networks; different generations of wireless systems. Not Offered 2019–20. Instructor: Staff.

EE 164. Stochastic and Adaptive Signal Processing. 9 units (3-0-6); third term. *Prerequisite:* ACM/EE/IDS 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 2019–20. Instructor: Hassibi.

CS/CNS/EE/IDS 165. Foundations of Machine Learning and Statistical Inference. 12 units (3-3-6). For course description, see Computer Science.

EE/CS/IDS 167. Introduction to Data Compression and Storage. 9 units (3-0-6); third term. *Prerequisites:* Ma 3 or ACM/EE/IDS 116. The course will introduce the students to the basic principles and techniques of codes for data compression and storage. The students will master the basic algorithms used for lossless and lossy compression of digital and analog data and the major ideas behind coding for flash memories. Topics include the Huffman code, the arithmetic code, Lempel-Ziv dictionary techniques, scalar and vector quantizers, transform coding; codes for constrained storage systems. Given in alternate years; Not offered 2019–20. Instructor: Kostina.

MedE/EE/BE 168 abc. Biomedical Optics: Principles and Imaging. 9 units (4-0-5). For course description, see Medical Engineering.

ACM/EE/IDS 170. Mathematics of Signal Processing. 12 units (3-0-9). For course description, see Applied and Computational Mathematics.

EE/CS/MedE 175. Digital Circuits Analysis and Design with Complete VHDL and RTL Approach. 9 units (3-6-0); third term. *Prerequisites:* medium to advanced knowledge of digital electronics. A careful balance between synthesis and analysis in the development of digital circuits plus a truly complete coverage of the VHDL language. The RTL (register transfer level) approach. Study of FPGA devices and comparison to ASIC alternatives. Tutorials of software and hardware tools employed in the course. VHDL infrastructure, including lexical elements, data types, operators, attributes, and

complex data structures. Detailed review of combinational circuits followed by full VHDL coverage for combinational circuits plus recommended design practices. Detailed review of sequential circuits followed by full VHDL coverage for sequential circuits plus recommended design practices. Detailed review of state machines followed by full VHDL coverage and recommended design practices. Construction of VHDL libraries. Hierarchical design and practice on the hard task of project splitting. Automated simulation using VHDL testbenches. Designs are implemented in state-of-the-art FPGA boards. Instructor: Pedroni.

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.

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 2019–20.

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 2019–20.

BE/EE/MedE 189 ab. Design and Construction of Biodevices. 189 a, 12 units (3-6-3) offered both first and third terms. 189b, 9 units (0-9-0) offered only third term. For course description, see Bioengineering.

ACM/EE/IDS 217. Advanced Topics in Stochastic Analysis. 9 units (3-0-6). For course description, see Applied and Computational Mathematics.

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

ME/EE/EST 109. Energy Technology and Policy. 9 units (3-0-6). For course description, see Mechanical Engineering.

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

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: Umans.

E/VC 88. Critical Making. 9 units (3-0-6); third term. This course examines the concepts and practices of maker culture through hands-on engagement, guest workshops, lectures, reading and discussions on the relations between technology, culture and society. Classes may include digital fabrication, physical computing, and other DIY technologies as well as traditional making. Major writings and practitioners' work may be covered from the study of maker culture, DIY culture, media, critical theory, histories of science, design and art. Not offered 2019–20. Instructor: Mushkin.

E/H/VC 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 Eadward 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. Instructor: Mushkin.

E 100. Special Topics in Engineering Applied Science. *Units to be arranged; terms to be arranged; offered by announcement. Prerequisites: none.* Content may vary from year to year, at a level suitable for advanced undergraduate or graduate students. Topics will be chosen to meet the emerging needs of students. Instructors: TBD.

E/SEC 102. Scientific and Technology Entrepreneurship. *9 units (3-0-6); third term.* This course introduces students to the conceptual frameworks, the analytical approaches, the personal understanding and skills, and the actions required to launch a successful technology-based company. Specifically, it addresses the challenges of evaluating new technologies and original business ideas for commercialization, determining how best to implement those ideas in a startup venture, attracting the resources needed for a new venture (e.g., key people, corporate partners, and funding), organizing and operating a new enterprise, structuring and negotiating important business relationships, and leading early stage companies toward “launch velocity”. Instructor: TBD.

E/SEC 103. Management of Technology. *9 units (3-0-6); first term.* A course intended for students interested in learning how rapidly evolving technologies are harnessed to produce useful products or fertile new area for research. Students will work through Harvard Business School case studies, supplemented by lectures to elucidate the key issues. There will be a term project where students predict the future evolution of an exciting technology. The course is team-based and designed for students considering choosing an exciting research area, 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 assess-

ment, technology trend methodologies (scenarios, projections), motivation, rewards and recognition. Industries considered will include electronics (hardware and software), aerospace, medical, biotech, etc. Students will perform both primary and secondary research and through analysis present defensible projections. E/ SEC 102 and E/ME/MedE 105 are useful but not required precursors. Instructor: TBD.

E/ME/MedE 105 ab. Design for Freedom from Disability. *9 units (3-0-6); terms to be arranged; offered by announcement.* 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. Instructor: TBD.

E 110. Principles of University Teaching and Learning in STEM. *3 units (2-0-1); first term, second term.* This graduate course examines the research on university-level STEM (science, technology, engineering, and mathematics) teaching and learning, which has been used to inform a well-established body of evidence-based teaching practices. 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 explore the roles of active learning, student engagement, and inclusive teaching practices in designing classes where all students have an equal opportunity to be successful and feel a sense of belonging, both in the course and as scientists. Readings will inform in-class work and students will apply principles to a project of their choice. Instructors: Horii, Weaver.

ENGLISH

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Hum/En 20. Greek Epic and Drama. *9 units (3-0-6).* For course description, see Humanities.

Hum/En 21. The Marvelous and the Monstrous: Literature at the Boundaries of the Real. *9 units (3-0-6).* For course description, see Humanities.

Hum/En 22. Inequality. *9 units (3-0-6).* For course description, see Humanities.

Hum/En 23. Literature and Medicine. 9 units (3-0-6). For course description, see Humanities.

Hum/En 24. The Scientific Imagination in English Literature. 9 units (3-0-6). For course description, see Humanities.

Hum/En 25. The Human Animal. 9 units (3-0-6). For course description, see Humanities.

Hum/En 29. Dream Narratives. 9 units (3-0-6). For course description, see Humanities.

Hum/En 33. Modern Metamorphoses. 9 units (3-0-6). For course description, see Humanities.

Hum/En 35. Major British Authors. 9 units (3-0-6). For course description, see Humanities.

Hum/En 36. American Literature and Culture. 9 units (3-0-6). For course description, see Humanities.

Hum/En 37. Modern European Literature. 9 units (3-0-6). For course description, see Humanities.

Hum/En 38. Telling Time in American Modernism. 9 units (3-0-6). For course description, see Humanities.

Hum/En 39. Contemporary American Fiction. 9 units (3-0-6). For course description, see Humanities.

En 83. History of the English Language. 9 units (3-0-6); *third 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 2019–20.

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.

En 85. Poetry Writing. *9 units (3-0-6); third term.* When William Blake wrote “to see a World in a Grain of Sand,” he tapped into poetry’s power to model the universe. For instance, once we set up a simile between “world” and “grain of sand”, we can test this hypothesis of sameness. How is sand like the world? Where will the model fail? And what might that tell us? Imagery, sensory language, arguments, ideas, and verse form itself can lead poetry toward power and discovery. This pursuit can reach from the page into one’s own life. We will work hard together on poems, our own and one another’s. Students may apply one term of 85, 86, or 89 to the additional HSS requirements, and all other courses in this series will receive institute credit. Instructors: Factor.

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, or 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. Students may apply one term of En 85, 86, or 89 to the additional HSS requirements, and all other courses in this series will receive Institute credit. 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 do 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. Not offered 2019–20.

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. Not offered 2019–20.

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. Not offered 2019–20.

En 106. Poetic Justice: Histories of Literature and Law. *9 units (3-0-6); third term.* How does literature help us to frame questions of equity and fairness? How do writers represent broad concepts like the “common good” or the “body politic,” and what does poetry do in the world to shape political action and ideas? This course takes the long historical view on these questions, exploring the overlapping histories of law and literary representation within premodern and contemporary contexts. We will ask how literature thinks about problems of justice, violence, and mercy, and how the courtroom becomes a key site for representing the dramas of social inclusion and exclusion. Possible authors and texts include Dante, Chaucer, Langland, Shakespeare, and Behn. Instructor: Jahner. Not offered 2019–20.

En 107. Medieval Romance. *9 units (3-0-6); second 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. Instructor: Jahner. Not offered 2019–20.

En/VC 108. Volcanoes. *9 units (3-0-6); first term.* Long before torrents of lava cascaded down Los Angeles streets in the 1997 film *Volcano*, volcanic disaster narratives erupted across 19th-century British pages, stages, and screens. This class will examine the enduring fascination with volcanoes in literary and visual culture and the socio-political tensions that disaster narratives expose. Students will analyze Mary Shelley’s *Frankenstein* and Tambora’s infamous 1815 eruption, James Pain’s 1880s pyrotechnic adaptation of Vesuvius’s 79AD eruption, and paintings of global sunsets after Krakatoa’s 1883 eruption. Additional literary and visual texts may include works by: Felicia Hemans, Isabella Bird, M.P. Shiel, Charles Dickens, Sir Edward Bulwer-Lytton, and J. M. W. Turner. Instructor: Sullivan.

En 109. Madness and Reason. *9 units (3-0-6); second term.* Madness threatens to dissolve boundaries of the most various kinds:

between the human and the inhumane, reality and fantasy, sickness and health. One of the tasks of a literary text is to subdue and contain madness through the construction of rational frameworks. How does a literary text accomplish this? Which strategies, such as the use of irony and humor, are the most effective? What role do insane characters play in literary texts? And when - if ever - should we consider an excess of reason as a kind of madness in its own right? Selected readings from Shakespeare, Voltaire, Goethe, Hoffmann, Büchner, Gogol, and Schnitzler, among others. Instructor: Holland.

En 110. Sinners, Saints, and Sexuality in Premodern Literature.

9 units (3-0-6); third term. What made the difference between saint and sinner in medieval and Renaissance literature? This class takes up this question by focusing on the unruly problems of embodiment. We will read across a wide range of literatures, including early medical texts, saints' lives, poetry and romance, as we examine how earlier periods understood gender and sexual difference.

Questions we may consider include the following: how did writers construct the "naturalness" or "unnaturalness" of particular bodies and bodily acts? How did individuals assert control over their own bodies and those of others? In what ways did writing authorize, scrutinize, or police the boundaries of the licit and illicit? Finally, how have modern critics framed these questions? Possible readings include Aristotle, Freud, Chaucer, Margery Kempe, Christine de Pizan, Sidney, Shakespeare. Instructor: Jahner. Not offered 2019–20.

En 113. Shakespeare's Career: Comedies and Histories.

9 units (3-0-6). The first of a two-course sequence on Shakespeare's career as a dramatist and poet. We will read plays from the first half of Shakespeare's career, his comedies and histories. Particular attention will be paid to Shakespeare's use of his sources and to the textual history of the plays. En 113 and En 114 may be taken independently and, usually, are taught in alternate years. Instructor: Pigman. Not offered 2019–20.

En 114. Shakespeare's Career: Tragedies and Tragicomedies.

9 units (3-0-6); third term. The second of a two-course sequence on Shakespeare's career as a dramatist and poet. We will read works from the second half of Shakespeare's career, his tragedies, tragicomedies, and Sonnets. Particular attention will be paid to Shakespeare's use of his sources and to the textual history of the plays. En 113 and En 114 may be taken independently and, usually, are taught in alternate years. Instructor: Pigman.

En/VC 117. Picturing the Universe.

9 units (3-0-6); second term. Whether you are a physicist, photographer, or bibliophile, grab a warm jacket. The night sky beckons. In addition to observing and photographing our own starry skies, we will study 19th-century

literary, artistic, and scientific responses to new understandings of the universe as dynamic, decentered, and limitless. In Victorian England, picturing the universe in literature and recording celestial light in photographs defied the physiological limitations of human observation and fueled larger debates about objective evidence and subjective documentation. Authors studied may include: Anna Laetitia Aikin, Keats, Byron, Tennyson, Hardy, Agnes Clerke, E. E. Barnard, Tracy Smith, and Dava Sobel. Instructor: Sullivan.

En 118. Classical Mythology. 9 units (3-0-6); *first 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. Not offered 2019–20.

En 119. Displacement. 9 units (3-0-6); *first 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 2019–20.

En 120. What Women Want: Desire and the Modern American Novel. 9 units (3-0-6); *second term*. The question of what a woman wants animates a central strain of the modern American novel, as do evolving ideas about what women can and cannot have. This course considers female desire-for personal agency and freedom, self- and sexual fulfillment, economic and social opportunity-across a half dozen novels written from about 1880 - 1940, in light of some of the cultural forces that shape and constrain characters' (and real women's) horizons. Authors covered may include Henry James, Edith Wharton, Theodore Dreiser, Anzia Yezierska, Nella Larsen, and Zora Neale Hurston. Instructor: Jurca.

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 Sopho-

cles' 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. Not offered 2019–20.

En 122. Early History of the Novel. *9 units (3-0-6); third term.* The realistic novel is a surprising, even experimental moment in the history of fiction. How and why did daily life become a legitimate topic for narrative in the 18th century? The realistic turn clearly attracted new classes of readers, but did it also make the novel a better vehicle for commenting on society at large? Why were the formal conventions of realistic writing so tightly circumscribed? Authors may include Cervantes, Defoe, Richardson, Fielding, Sterne, Walpole, Boswell, and Austen. Not offered 2019–20.

En 123. The 19th-Century English Novel. *9 units (3-0-6); first 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 2019–20.

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 2019–20.

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. Not offered 2019–20.

En 126. Gothic Fiction. *9 units (3-0-6); second 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 2019–20.

En 127. Jane Austen. *9 units (3-0-6); second 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. Instructor: Gilmartin.

En 128. Modern and Contemporary Irish Literature. *9 units (3-0-6); first 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. Not offered 2019–20.

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 2019–20.

En 134. The Career of Herman Melville. *9 units (3-0-6); third term.* The course will analyze Melville's career starting with *Typee* and ending with *Billy Budd*. Special attention will be given to *Moby-Dick* and *Pierre*. The centrality of Melville's position in American literature will be considered from a variety of perspectives, including aesthetics, representations of race, class, and gender, the role of the audience, and connections with other authors. Instructor: Weinstein.

En 135. Dickens's London. *9 units (3-0-6); third term.* Charles Dickens and London have perhaps the most famous relationship of any writer and city in English. In this course, we will investigate

both the London Dickens knew, and the portrait of the city that he painted, by reading some of Dickens's great mid-career novels alongside a selection of primary and secondary historical sources. We will think about the gap-or overlap- between history and fiction, the idea of the novelist as alternative historian, and the idea of the novel as historical document. Historical topics covered may include: the development of the Victorian police force; plague and public health; Victorian poverty; colonialism and imperialism; Dickens and his illustrators; Victorian exhibition culture; and marriage and the cult of domesticity, among others. In addition to written work, students should expect to be responsible for making a short research presentation at some point in the term. Instructor: Gilmore. Not offered 2019–20.

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 2019–20.

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 2019–20.

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 2019–20.

En 139. Reading Resistance in Cold War American Literature. *9 units (3-0-6); first term.* This course will examine the complexities and contradictions of US Cold War culture. Through literary texts featuring a diverse range of protagonists, we will engage characters who question the status quo, often by exploring the limits and exclusions of national belonging in this period. Though the 1950s saw the rise of McCarthyism and the threat of nuclear war, landmark events in these years also galvanized the civil rights

movement and demands for social justice. Course readings in Cold War fiction, drama, and poetry will demonstrate how mainstream social identities conditioned by racial, class, gender and sexual norms, were being challenged and subverted in ways that would intensify and take on collective expression in the 1960s. Authors studied may include: Gwendolyn Brooks, William Demby, Lorraine Hansberry, Jack Kerouac, William S. Burroughs, Carson McCullers, Mitsuye Yamada, Sylvia Plath, and John Okada. Instructor: Sherazi. Not offered 2019–20.

En 140. African American Expatriate Culture in Postwar Europe. *9 units (3-0-6); first term.* In the years following World War II, an unprecedented number of African American writers, artists, and intellectuals moved to Paris and Rome, many seeking greater personal liberties and a refuge from racial discrimination at home. As we explore literature, nonfiction, and visual culture created by African Americans in postwar Europe, we will consider how and why the postwar creative scene in Paris differed from that of Rome. We will analyze postwar African American expatriate writing's critical perspectives and insights regarding American society and culture, particularly regarding desegregation and postwar social identities. Our discussions will identify the literary strategies that writers used to address the changing times, promote social justice, and advance new narrative forms, often by crossing traditional boundaries of genre and nation. Authors studied may include: James Baldwin, Richard Wright, Barbara Chase-Riboud, William Demby, Maya Angelou, and Ralph Ellison. Instructor: Sherazi. Not offered 2019–20.

En 141. Contemporary African American Literature. *9 units (3-0-6); first term.* This course will engage works of contemporary African American literature, including Ishmael Reed's experimental novel *Mumbo Jumbo* (1972) and Octavia Butler's time-travel novel *Kindred* (1979) and selected Afrofuturist short stories. We will read critical essays about temporality and consider these authors' use of temporal strategies, including anachronisms, non-linear narration, historiography, and the creation of speculative worlds. How does the artistic project of narrating the racialized past create possibilities for imagining alternative futures? The course will analyze the role of slavery, trauma, and collective memory in our readings, and it will set these literary texts in conversation with Afrofuturist music and visual culture from the 1970s to the present. Students will have the opportunity to examine archival materials from the Huntington Library related to Octavia Butler's published fiction. Instructor: Sherazi. Not offered 2019–20.

En 142. Post-1945 American Literature and 'The Death of the Author'. *9 units (3-0-6); first term.* This course will explore the ambiguous status of literature that is published in the wake of an author's death. Should "unfinished" work be edited and published

in the late author's name? What if the author left behind no express wishes for her/his unpublished writing or asked that it be destroyed? Alongside such questions, we will analyze posthumously published post-1945 American literature's formal features and its engagements with socio-political transformations related to race, class, gender, and sexuality. Course readings will include Roland Barthes' "The Death of the Author" (1967) and Michel Foucault's "What is an Author?" (1969), as well as posthumously published modernist fiction and poetry by authors including Ralph Ellison, Sylvia Plath, Jack Kerouac and William Burroughs. Instructors: Sherazi.

En 150. Chaos and Literature. 9 units (3-0-6); second term. We tend to think of literary texts as models of a stable poetic order, but modern and postmodern writers conduct increasingly bold experiments to test the contrary. This class explores how writers from the nineteenth century onward draw upon ancient and contemporary concepts of chaos to test out increasingly sophisticated models of disorder through writing. Readings to include Lucretius, Serres, Calvino, Barth, Stoppard, and Kehlmann. Instructor: Holland. Not offered 2019–20.

En/VC 160 ab. Classical Hollywood Cinema. 9 units (3-0-6); second term. This course introduces students to Hollywood films and filmmaking during the classical period, from the coming of sound through the '50s. Students will develop the techniques and vocabulary appropriate to the distinct formal properties of film. 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. Part b not offered 2019–20. Instructor: Jurca.

En/VC 161. The New Hollywood. 9 units (3-0-6); first 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 especially in the representation of violence and sexuality. 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. Not offered 2019–20.

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 2019–20.

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 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 2019–20.

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 criti-

cally to give a sense of the totality of this greatest British regional novelist's achievement. Not offered 2019–20.

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. Not offered 2019–20.

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 2019–20.

En 186. The Novel of Education. 9 units (3-0-6); *third term*. This class takes up a set of mostly very funny, mostly 20th century British novels to frame a simple-seeming, yet deceptively complicated set of questions: What does it mean to be educated? Who has

access to education? What does an ideal education consist in? And ultimately: What is a university for? As we think through these questions we will read op/eds and investigative journalism in addition to fiction, and we will consider a variety of university-centered topics (determined by student interest) including issues of gender, class, privilege, race, and genius. Authors read may include Sayers, Larkin, Amis, C.P. Snow, Lodge, 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. Not offered 2019–20.

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 2019–20.

En/H 193. Cervantes, Truth or Dare: Don Quixote in an Age of Empire. *9 units (3-0-6); first 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. Not offered 2019–20.

ENGLISH AS A SECOND LANGUAGE

Please see page 324 for requirements regarding English competency. All of the following courses are open to international graduate students only.

ESL 101 ab. Oral Communication and Presentation. *3 units (3-0-0); first, second terms.* This course focuses on preparing non-native speakers of English with the communication skills necessary to organize, present or exchange information in a clear, concise manner to a variety of audiences. ESL 101a will provide instruction on the development of pronunciation, intonation patterns and stress, grammar and verb tense, listening comprehension, and fluency in speaking. Aspects of American culture as well as come current events will be discussed. ESL 101b is a continuation of ESL 101a, and covers a variety of oral presentation skills. Students will be asked to paraphrase, summarize, and synthesize information from a journal article or in-class discussions and communicate ideas to the class. The class will discuss information from readings and other media sources in small groups to collect and organize ideas for discussion. ESL 101ab is open to all first-year graduate students and may be required for some students designated by the ESL interview process during Orientation. A passing grade will satisfy the Institute English proficiency requirement for candidacy. Graded pass/fail. Instructor: Staff.

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ESL/Wr 107. Graduate Writing Seminar. *6 units (3-0-3); third term.* This course provides guided instruction in academic writing in STEM fields. More specifically, it teaches graduate students about composing texts in scientific English for expert audiences. It helps familiarize writers with academic STEM discourse, and it teaches writers about the style and genres of U.S. academic STEM writing, helping them learn to locate, read, and write about the work of others in their field. From here, students learn to review the literature in their fields and situate their own research goals within that context. Students are encouraged to take ESL/Wr 107 in the first or second year of graduate school. This course is designed for non-native

speakers of English, but it covers topics that are relevant to native English speakers. Instructor: Staff.

ESL/Wr 108. Intermediate Graduate Writing Seminar. *6 units (3-0-3); summer term.* This course focuses on strategies for composing an academic journal article in a STEM field. The rhetorical purpose and form of each section of the journal article will be considered in depth. The course is intended for graduate students who are prepared to be a lead author on a manuscript. While the course will cover strategies for collaborative writing, students will be asked to draft sections of an original journal article based upon their own research. The course will also provide instruction on selecting a target journal, preparing a manuscript for submission, and responding to feedback from peer reviewers. Clarity in scientific writing and creating effective figures will also be discussed. This course is designed for non-native speakers of English, but it covers topics that are relevant to native English speakers. Course enrollment is limited to 15 students. Instructor: Staff.

ENVIRONMENTAL SCIENCE AND ENGINEERING

ESE 1. Earth's Climate. *9 units (3-0-6); third term.* An introduction to the coupling between atmospheric composition and climate on Earth. How Earth's climate has changed in the past and its evolving response to the rapid increase in carbon dioxide and methane happening today. Model projections of future climate and associated risks. Development of climate policies in face of uncertainty in these projections and risks. Enrollment is limited. Satisfies the menu requirement of the Caltech core curriculum. Juniors and Seniors who have satisfied their menu course requirement should enroll in ESE 101. Instructor: Wennberg.

FS/ESE/Ge 18. Freshman Seminar: The Unseen Microbial World in Plain Sight. *6 units (2-0-4).* For course description, see Freshman Seminars.

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.* Introduction to the fundamental processes governing atmospheric circulations and climate. Starting from an overview of the observed state of the atmosphere and its variation over the past, the course discusses Earth's radiative energy balance including the greenhouse effect, Earth's orbit around the Sun and climatic effects of its variations, and the role of atmospheric circulations in maintaining the energy, angular momentum, and water balances, which determine the distributions of temperatures, winds, and precipitation. The focus throughout is on order-of-magnitude physics that is applicable to climates generally, including those of Earth's past and future and of other planets. Instructor: Schneider.

ESE 102. Earth's Oceans. 9 units (3-0-6); *first term.* This course will provide a basic introduction to physical, chemical and biological properties of Earth's ocean. Topics to be covered include: oceanographic observational and numerical methods as well as the phenomenology and distribution of temperature, salinity, and tracers. Fundamentals of ocean dynamics, such as Ekman layers, wind-driven gyres, and overturning circulations. Ocean biology and chemistry: simple plankton population models, Redfield ratios, air-sea gas exchange, productivity and respiration, carbon cycle basics. Changes in ocean circulation over Earth's history and its impact on past climate changes. Instructor: Thompson.

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: Frankenberg.

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: Thompson.

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: Frankenberg.

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

BEM/Ec/ESE 119. Environmental Economics. 9 units (3-0-6). For course description, see Business, Economics, and Management.

ESE 130. Introduction to Atmosphere and Ocean Dynamics. 9 units (3-0-6); second term. Prerequisites: ESE 101/102 or instructor's permission. Introduction to geophysical fluid 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: Callies.

ESE 131. Ocean Dynamics. 9 units (3-0-6); third term. Prerequisites: ESE 130 or instructor's permission. This course gives an in-depth discussion of the fluid dynamics of the world ocean. Building on the concepts developed in ESE 130, this course explores the vertical structure of the wind-driven gyre circulation, thermocline theory, eddies and eddy parameterizations, the circulation of the deep ocean, ocean energetics, surface gravity waves, tides, internal waves, and turbulent mixing. Instructors: Callies, 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. Instructor: Staff. Not offered 2019–20.

ESE 133. Global Atmospheric Circulations. 9 units (3-0-6); second term. Prerequisites: ESE 130 or instructor's permission. Introduction to the global-scale fluid dynamics of atmospheres, beginning with a phenomenological overview of observed circulations on Earth and other planets and leading to currently unsolved problems. Topics include constraints on atmospheric circulations and zonal winds from angular momentum balance; Rossby wave generation,

propagation, and dissipation and their roles in the maintenance of global circulations; Hadley circulations and tropical-extratropical interactions; energy cycle and thermodynamic efficiency of atmospheric circulations. The course focuses on Earth's atmosphere but explores a continuum of possible planetary circulations and relationships among them as parameters such as the planetary rotation rate change. Instructor: Staff. Not offered 2019–20.

ESE 134. Cloud and Boundary Layer Dynamics. 9 units (3-0-6); third term. Prerequisites: ESE 130 or instructor's permission. Introduction to the dynamics controlling boundary layers and clouds and how they may change with climate, from a phenomenological overview of cloud and boundary layer morphologies to closure theories for turbulence and convection. Topics include similarity theories for boundary layers; mixed-layer models; moist thermodynamics and stability; stratocumulus and trade-cumulus boundary layers; shallow cumulus convection and deep convection. Instructor: Schneider. Offered 2019–20.

ESE 135. Topics in Atmosphere and Ocean Dynamics. 6 units (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. Instructor: Callies. Not offered 2019–20.

ESE 136. Climate Models. 6 units (2-0-4); third term. Prerequisites: ESE 101 or instructor's permission. Introduction to climate models, from numerical methods for the underlying equations of motion to parameterization schemes for processes such as clouds, sea ice, and land hydrology. The course will move from an overview of modeling concepts to the practice of climate modeling, with hands-on exercises in running a climate model and analyzing and understanding its output. It will enable students to design their own model experiments and to evaluate modeling results critically. Instructor: Schneider. Not offered 2019–20.

ESE 137. Polar Oceanography. 9 units (3-0-6); third term. Prerequisites: ESE 131 or instructor's permission. This course focuses on high latitude processes related to the Earth's oceans and their interaction with the cryosphere, including glaciers, ice shelves and sea ice. The course starts with introductory lectures related to regional circulation features, water mass modification and ice dynamics. A single topic will be selected to explore in detail through the scientific literature and through individual projects. Instructor: Thompson. Given in alternate years; Offered 2019–20.

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 feedback 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. Instructor: Staff. Not offered 2019–20.

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

Ge/ESE 140 c. Stable Isotope Biogeochemistry. 9 units (3-0-6). For course description, see Geological and Planetary Sciences.

ESE/Ge 142. Aquatic Chemistry of Natural Waters. 9 units (3-0-6); third term. Prerequisites: Ch 1 or instructor's permission. Inorganic chemistry of natural waters with an emphasis on equilibrium solutions to problems in rivers, lakes, and the ocean. Topics will include, acid-base chemistry, precipitation, complexation, redox reactions, and surface chemistry. Examples will largely be drawn from geochemistry and geobiology. Selected topics in kinetics will be covered based on interest and time. Instructor: Adkins.

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

ESE 144. Climate from Space. 9 units (3-0-6); second term. Introduction to satellite remote sensing. Earth's energy balance. Atmospheric physics and composition. Ocean dynamics and ice physics from space. The water, energy and carbon cycles. The Earth's biosphere from space. The climate system. Instructors: Teixeira, Thompson.

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. Paleoceanography. 9 units (3-0-6). For course description, see Geological and Planetary Sciences.

ESE 156. Remote Sensing of the Atmosphere and Biosphere.

9 units (3-0-6); first term. An introduction into methods to quantify trace gases as well as vegetation properties remotely (from space, air-borne or ground-based). This course will provide the basic concepts of remote sensing, using hands-on examples to be solved in class and as problem-sets. Topics covered include: Absorption spectroscopy, measurement and modeling techniques, optimal estimation theory and error characterization, applications in global studies of biogeochemical cycles and air pollution/quality. This course is complementary to EE/Ae 157ab and Ge/EE/ESE 157c with stronger emphasis on applications for the atmosphere and biosphere. Students will work with real and synthetic remote sensing data (basic knowledge of Python advantageous, will make use of Jupyter notebooks extensively). Instructor: Frankenberg.

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);*

second term; Open to graduate students and seniors with instructor's permission. Fundamentals of aerosol physics and chemistry; aerodynamics and diffusion of aerosol particles; condensation and evaporation; thermodynamics of particulate systems; nucleation; coagulation; particle size distributions; optics of small particles. Instructors: Seinfeld, Flagan. Not offered 2019–20.

ESE/Bi 166. Microbial Physiology. *9 units (3-1-5); first term.*

Recommended prerequisite: one year of general biology. A course on growth and functions in the prokaryotic cell. Topics covered: growth, transport of small molecules, protein excretion, membrane bioenergetics, energy metabolism, motility, chemotaxis, global regulators, and metabolic integration. Instructor: Leadbetter.

ESE/Bi 168. Microbial Metabolic Diversity. *9 units (3-0-6); second*

term. Prerequisites: ESE 142, ESE/Bi 166. A course on the metabolic diversity of microorganisms. Basic thermodynamic principles governing energy conservation will be discussed, with emphasis placed on photosynthesis and respiration. Students will be exposed to genetic, genomic, and biochemical techniques that can be used to elucidate the mechanisms of cellular electron transfer underlying these metabolisms. Instructor: Newman. Given in alternate years; not offered 2019–20.

Ge/ESE/Bi 178. Microbial Ecology. *9 units (3-2-4).* For course description, see Geological and Planetary Sciences.

ESE/Ge/Ch 171. Atmospheric Chemistry I. *9 units (3-0-6); third term. Prerequisite: Ch 1 or equivalent.* A detailed course about

chemical transformation in Earth's atmosphere. Kinetics, spectroscopy, and thermodynamics of gas-phase chemistry of the stratosphere and troposphere; sources, sinks, and lifetimes of trace atmospheric species; stratospheric ozone chemistry; oxidation mechanisms in the troposphere. Instructors: Seinfeld, Wennberg. Offered 2019–20.

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. Instructors: Seinfeld, Wennberg. Not offered 2019–20.

ESE/Ch 175. Physical Chemistry of Engineered 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 engineered water systems and related water treatment processes. Lectures cover basic principles of physical-organic and physical-inorganic chemistry relevant to the aquatic environment under realistic conditions. Specific topics include acid-base chemistry, metal-ligand chemistry, redox reactions, photochemical transformations, biochemical transformations, heterogeneous surface reactions, catalysis, and gas-transfer dynamics. The primary emphasis during the winter term course will be on the physical chemistry of engineered waters. Instructor: 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 aequated 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. Instructor: 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

(For course descriptions, please see Visual Culture page 735)

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. Not offered 2019–20.

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. Not offered 2019–20.

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 2019–20.

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: Beyond Physics. *6 units (2-0-4); second, third terms of freshman year and first term of sophomore year.* Freshmen are offered the opportunity to enroll in this class by submitting potential solutions to problems posed in the fall term. A small number of solutions will be selected as winners, granting those students permission to register. This course demonstrates how research ideas arise, are evaluated, and tested and how the ideas that survive are developed. Weekly group discussions and one-on-one meetings with faculty allow students to delve into cutting edge scientific research. Ideas from physics are used to think about a huge swath of problems ranging from how to detect life on extrasolar planets to exploring the scientific underpinnings of science fiction in Hollywood films to considering the efficiency of molecular machines. Support for summer research at Caltech between freshman and sophomore years will be automatic for students making satisfactory progress. Graded pass/fail. Freshmen only; limited enrollment. Instructor: Phillips.

FS/Ma 12. Freshman Seminar: The Mathematics of Enzyme Kinetics. *6 units (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. Instructor: Ramakrishnan.

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. Not offered 2019–20.

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. Not offered 2019–20.

FS/ESE/Ge 18. Freshman Seminar: The Unseen Microbial World in Plain Sight. *6 units (2-0-4); first term.* To paraphrase a Caltech engineering colleague: "In terms of Earth and the Environment, although fascinating, until recently our species had been nothing more than the hood ornament on a really interesting car. We should be studying what's under the hood, the microbial world, if we want to understand the engine". We will examine striking examples of microbes and microbial activities in the environment. There is one required field trip to visit sites of microbial interest somewhere in southern California. Freshmen only; limited enrollment. Instructor: Leadbetter.

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. 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: Thompson.

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. The causes and recent history of climate change. The course includes an overnight 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: Wernicke.

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 Seminars.

FS/ESE/Ge 18. Freshman Seminar: The Unseen Microbial World in Plain Sight. 6 units (2-0-4). For course description, see Freshman Seminars.

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 overnight field trip, selected laboratory exercises, and problem sets. Instructor: Wernicke.

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. 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. *Units to be arranged.* Practice in the effective organization and the delivery of oral presentation of scientific results before groups. Units and scheduling are done by the individual options. Graded pass/fail. Instructor: Staff.

Ge 110. Geographic Information System for Geology and Planetary Sciences. 3 units (0-3-0); first term. Formal introduction to modern computer-based geospatial analysis. Covers methods and applications of Geographic Information Systems (GIS) in Earth and planetary sciences in the form of practical lab exercises using the ArcGIS software package and a variety of geo-referenced data (Digital Elevation Models, geodetic measurements, satellite images, geological maps). Not offered 2019–20.

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); third 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 sedimen-

tary 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 2019–20.

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 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, the use of the petrographic microscope, and optical methods of mineral identification. 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. Instructor: Stolper. Given in alternate years; offered 2019–20.

Ge 115 b. Petrology and Petrography: Metamorphic Petrology. 9 units (3-3-3); second term. Prerequisites: Ge 114 ab. The mineralogical 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. Instructor: Eiler. Given in alternate years; not offered 2019–20.

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. Bayesian Statistics and Data Analysis. 9 units (3-0-6); second term. *Prerequisites:* CS1 or equivalent. 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. Instructor: Knutson.

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: Staff. Not offered 2019–20.

Ge 120 a. Field Geology: Introduction to Field Geology. 9 units (1-6-2); third term. *Prerequisites:* Ge 11 ab, Ge 106 (may be taken concurrently with Ge 106). A comprehensive introduction to methods of geological field mapping 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: Bucholz.

Ge 120 b. Field Geology: Summer Field Camp. 15 units (0-15-0); summer. *Prerequisites:* Ge 120 a or instructor's permission. Intensive three-week field course in a well-exposed area of the western United States covering techniques of geologic field observation, mapping, analysis, and report preparation. Field work begins in mid-June after Commencement Day. Instructor: Bucholz.

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), Stock (b), Grotzinger (c).

Ge 122 abc. Field Geology Seminar. 6 units (1-3-2); first, second, third terms. 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. Topic: tbd. Graded pass/fail. Instructor: Stock. Not offered 2019–20.

Ge 123. Continental Crust Seminar. 3 units (1-0-2); third term. A seminar course focusing on a topic related to the continental crust, which will be decided depending on the interest of participating students. Potential topics include arc magmatism, the evolution of the composition of continental crust through time, formation of granites, or specific localities/regions that help shape our understanding of continental crust generation. The course will comprise weekly student-lead discussion of scientific journal articles. Instructor: Bucholz.

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. Instructor: Kirschvink. Given in alternate years; not offered 2019–20.

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 paleomagnetic techniques to the determination of the history of the geomagnetic field. Instructor: Kirschvink. Given in alternate years; not offered 2019–20.

Ge 125. Geomorphology. 12 units (3-5-4); first term. Prerequisite: Ge 11 a or instructor's permission. A quantitative examination of landforms, runoff generation, river hydraulics, sediment transport, erosion and deposition, hillslope creep, landslides and debris flows, glacial processes, and submarine and Martian landscapes. Field and laboratory exercises are designed to facilitate quantitative measurements and analyses of geomorphic processes. Instructor: Lamb. Not offered 2019–20.

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. Offered 2019–20.

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. Instructor: Burnett. Given in alternate years; offered 2019–20.

Ge/Ch 128. Cosmochemistry. 9 units (3-0-6); first 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. Instructor: Blake. Given in alternate years; offered 2019–20.

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. Instructor: Blake. Given in alternate years; not offered 2019–20.

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: Batygin.

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. Instructor: Batygin.

Ge/ESE 139. Introduction to Atmospheric Radiation. 9 units (3-0-6); second term. Prerequisites: Ma 2, Ph 2, or instructor's permission. The basic physics of absorption and scattering of light by molecules, aerosols, and clouds. Theory of radiative transfer. Band models, correlated-k distributions and other approximate methods. Solar insolation, thermal emission, heating rates and radiances. Applications to Earth, Planets and Exoplanets. 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. Instructor: Eiler. Taught in odd years; alternates with Ge 140b. Not offered 2019–20.

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, with emphasis on the applications of these systems, from dating to forensic. Topics to be covered include nucleosynthesis, radioactive decay phenomena, geochronology, geochronometry, isotopes as tracers of solar system and planetary evolution, extinct radioactivities, cosmogenic isotopes and forensic geochemistry. Instructor: Tissot. Taught in even years; alternates with Ge 140a. Offered 2019–20.

Ge/ESE 140 c. Stable Isotope Biogeochemistry. 9 units (3-0-6); *third term. Prerequisites: Ge 140a or equivalent.* An introduction to the use of stable isotopes in biogeochemistry, 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. Offered 2019–20.

Ge 141. Isotope Cosmochemistry. 9 units (3-0-6); *first term.* An introduction to the study of the origin, abundances and distribution of the elements and their isotopes in the Universe, with emphasis on isotopic constraints into the conditions, events and processes that shaped our Solar System. Topics to be covered include: cosmology and the age of the Universe, the age of the Milky Way and the duration of nucleosynthesis, the fundamentals of isotopic fractionations, the key roles of isotopic anomalies in understanding Solar System dynamics, early Solar System chronology from short- and long-lived nuclei, chondritic meteorite components as clues to solar nebula and asteroid evolution, as well as planetary formation and chronology (e.g., Moon, Mars, Earth). Instructor: Tissot. Not offered 2019–20.

ESE/Ge 142. Aquatic Chemistry of Natural Waters. 9 units (3-0-6); *third term.* For course description, see Environmental Science and Engineering.

Ge/ESE 143. Organic Geochemistry. 9 units (3-2-4); *third 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. Instructor: Sessions. Not offered 2019–20.

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. Taught in odd-numbered years; offered 2019–20.

Ge/ESE 149. Marine Geochemistry. *9 units (3-0-6); second term.* *Prerequisites: 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. Instructor: Adkins. Given in alternate years; offered 2019–20.

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. Paleoclimatology. 9 units (3-0-6); second 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; not offered 2019–20.

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. Analysis of electromagnetic radiation at visible, infrared, and radio wavelengths for interpretation of the 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 does not require but is complementary to EE 157ab with 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. Not offered 2019–20.

Ge/Ay 159. Astrobiology. 9 units (3-0-6); second term. We approach the age-old questions “Why are we here?” and “Are we alone?” by covering topics in cosmology, the origins of life, planetary habitability, the detection of biosignatures, the search for extraterrestrial intelligence, and humanity’s future in space. Specific topics include: the emergence of life at hydrothermal vents; the habitable zone and the Gaia hypothesis; the search for ancient habitable environments on Mars; icy satellites like Europa, Enceladus, and Titan as astrobiological prospects; and the hunt for atmospheric biosignatures on exoplanets. Instructor: Yung. Given in alternate years; not offered 2019–20.

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); second 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: Zhan.

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); first 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 and Seismic Imaging. 9 units (3-0-6); first term. Prerequisites: basic linear algebra and Fourier transforms. Introduction to modern digital analysis: discrete Fourier transforms, filters, correlation, convolution, deconvolution and autoregressive models. Imaging with seismic reflection and refraction data, tomography, receiver functions and surface waves. Instructor: Clayton. Offered 2019–20.

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. Instructor: Staff. Given in alternate years; not offered 2019–20.

Ge 167. Tectonic Geodesy. 9 units (3-0-6); second 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 2019–20.

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.

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. Offered in alternate years; offered 2019–20.

Ge/ESE/Bi 178. 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 2019–20. Instructor: Orphan.

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 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 this 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 geobiological sciences. Students may enroll for any or all terms of this 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; second term. 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/or 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. Instructor: Staff.

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 2019–20.

Ge 214. Spectroscopy of Minerals. 9 units (3-0-6); third term. *Prerequisites:* Ge 114 a, Ch 21 ab, or instructor's permission. An overview of the interaction of minerals with electromagnetic radiation from gamma rays to microwaves. Particular emphasis is placed on visible, infrared, Raman, and Mössbauer spectroscopies as applied to mineralogical problems such as phase identification, chemical analysis, site populations, and origin of color and pleochroism. Instructor: Rossman. Given in alternate years; not offered 2019–20.

Ge 215. Topics in Advanced Petrology. 9 units (3-0-6); 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. Instructor: Asimow. Given in alternate years; not offered 2019–20.

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 2019–20.

Ge 219. Non-traditional Isotopes Seminar. 6 units (2-0-4); third term. *Prerequisites:* Ge 140a or b, or permission of instructor. The course deals with advanced topics in stable and radiogenic isotope geo-/cosmochemistry and builds on Ge 140a and b, with emphasis on non-traditional isotope systems (Mg, Fe, Ti, Mo, U, etc.). Starting with close examination of seminal papers, each topic will build up to a discussion of the remaining outstanding questions. Topics to be covered will be guided by class interests. Example subjects could include: the early solar system, extinct radioactivities, nucleosynthetic anomalies, the early Earth, paleoredox reconstructions, medical use of stable isotopes. All participants will lead discussions of papers and present a lecture on a relevant subject. Grades will include participation, a review/proposal paper, and oral examination(s). Instructor: Tissot.

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/Ge 225. Special Topics in Solid Mechanics. Units to be arranged. For course description, see Aerospace.

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); second term. 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: Zhan.

Ge 263. Computational Geophysics. 9 units (3-0-6); first term. *Prerequisites:* introductory class in geophysics, class in partial differential equations, some programming experience. Finite-difference, pseudo-spectral, finite-element, and spectral-element methods will be presented and applied to a number of geophysical problems including heat flow, deformation, and wave propagation. Students will program simple versions of methods. Instructors: Clayton, Gurnis. Given in alternate years; not offered 2019–20.

Ge 264. Machine Learning in Geophysics. 9 units (3-0-6); third term. *Prerequisites:* Ge 118 or equivalent. An overview of machine learning algorithms and their usage in current geophysical research. Both supervised and unsupervised learning will be covered. Algorithms include deep neural networks, ensemble learning, clustering, and dimensionality reduction. The course will address data requirements, current limitations, and the role of machine learning in the future of geophysics. Instructor: Ross.

Ae/AM/CE/ME/Ge 265 ab. Static and Dynamic Failure of Brittle Solids and Interfaces, from the Micro to the Mega. 9 units; (3-0-6). For course description, see Aerospace.

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

Bi/BE/Ch/ChE/Ge 269. Integrative Projects in Microbial Science and Engineering. 6 units (3-0-3). For course description, see Biology.

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; not offered 2019–20.

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. Given in alternate years; offered 2019–20.

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. American History. 9 units (3-0-6). For course description, see Humanities.

Hum/H 2. Which Side Are You On? 20th Century African American History Through Debate. 9 units (3-0-6). For course description, see Humanities.

Hum/H 3. The United States in the Twentieth Century. 9 units (3-0-6). For course description, see Humanities.

Hum/H 5. The History of the Chinese Empire. 9 units (3-0-6). For course description, see Humanities.

Hum/H 8 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 8 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 8 c. Civilization, Science, and Archaeology: The Nature of Religious Beliefs in Ancient Egypt, Mesopotamia, and Israel and the Nature of Religious Belief. 9 units (3-0-6). For course description, see Humanities.

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

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

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

Hum/H 10. Medieval Europe: The Problem of Violence. 9 units (3-0-6). For course description, see Humanities.

Hum/H 11. Love and Death: Using Demography to Study the History of Europe from 1700. 9 units (3-0-6). For course description, see Humanities.

Hum/H/HPS 18. Introduction to the History of Science. 9 units (3-0-6). For course description, see Humanities.

H 60. Reading in History. *Units to be determined for the individual by the division; 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.

E/H/VC 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. Not offered 2019–20.

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. Not offered 2019–20.

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 2019–20.

H 111. The Medieval Church. *9 units (3-0-6); first 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. Instructor: Brown. Not offered 2019–20.

H 112. The Vikings. *9 units (3-0-6); second 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 did they differ from the Scandinavian and north German pirates and raiders who preceded them? Were they really the horned-helmeted, bloodthirsty barbarians depicted by modern popular media and by many medieval chronicles? What effect did they have in their roughly two centuries of raiding and colonization on the civilizations of medieval and ultimately modern Europe? Instructor: Brown.

H 115 abc. British History. *9 units (3-0-6); second term.* 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. Part a and c not offered in 2019–20. Instructor: Styles.

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 2019–20.

H 123. Ordinary People: Uncovering Everyday Life in the European Past. *9 units (3-0-6); second term.* In the historical record, much attention is given to wealthy elites (rulers and lawmakers, aristocrats, wealthy merchants), since they were the ones who left written records of their political and economic activities and their personal affairs. But what about the vast majority of people who lived in the past, most of whom were barely literate and had little opportunity to 'make history'? What can we know about them? This class focuses on the lives of ordinary people, and the sources historians use to learn about them. Special attention will be given to women, the poor, and other marginalized groups in societies ranging from England in the west to Russia in the east. Instructor: Dennison.

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 understanding of these basic events can thus shed light on the economic and social world inhabited by people in the past. In this course students will be introduced to the sources and methods used by historical demographers to construct demographic measures for past populations. In addition, the course will cover a broad range of problems in historical demography, including mortality crises, fertility control, infant mortality, and the role of economic and social institutions in demographic change. While the

emphasis is on societies in the past, there will be some discussion of modern demographic trends in various parts of the world. Not offered 2019–20.

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. Not offered 2019–20.

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 postmodern theorists, which provide intellectual underpinning for experimenting with new forms of history. Not offered 2019–20.

H 131. History of Extinction. *9 units (3-0-6); first term.* Humans are in the midst of the sixth mass extinction—the first to be caused by human activity. Extinction has been viewed in changing ways over the past 200 years, and this course takes an interdisciplinary approach to learning about the extinction process from a historical as well as a modern perspective. Our focus will be on the extinction of biological entities, but we will also touch on other systems that have disappeared: languages, technologies, habitats, and ways of living. Central to our endeavors will be asking what it means to live in this time of loss: Should we mourn? And if so, how do we mourn for what many or most of us do not see, but only read about? Finally, we will scrutinize what the practical effects of extinction have been, are, and will be. We will also make at least one visit to a natural history museum to view some extinct species behind the scenes. Instructor: Lewis. Not offered 2019–20.

H 132. Humanistic Ecology. *9 units (3-0-6); third term.* Humans’ conceptions of nature have changed dramatically over time. Ecological systems influence human culture, politics, law, and many other spheres, and in turn, humans influence those systems. This class introduces students to the field of humanistic ecology—a

discipline that looks to a number of cultural, political, historical and economic elements to better understand the role of ecology in a larger sphere outside of its scientific structure and uses. Humanistic ecology is designed to provide context for the study of ecology, and in a fundamental way, focuses on the appropriate role of humanity in its relationship to nature: what is ethical, or not, what is useful, or not, and a variety of other matters that should be considered when taking a fully three-dimensional view of ecological science. Instructor: Lewis. Not offered 2019–20.

H 133. Forests and Humans. *9 units (3-0-6); first term.* Forests - which cover 31 percent of the world's land surface - have played essential roles in enhancing the planet's biodiversity. Forests have also served humans in numerous and often controversial ways, and have also been subjected to dramatic change through human activity. How well have we served forests, as well as being served by them? The class will cover the growth and use of forests from a humanistic and historic perspective, as well as discussions about the role of fire in forests, with a particular emphasis on the unprecedented forest fires in California in the past several years and the global ecological implications. Instructor: Lewis.

H 134. Birds, Evolution, Speciation and Society. *9 units (3-0-6); third term.* The cultural, scientific, social and political roles of birds make them an excellent lens through which to view humans' interactions with the natural world. This course will cover our changing understandings of birds, starting with hawking and falconry in earlier centuries, through the discovery of new species, up through Darwinian understandings of speciation and evolution, and continuing up to present scientific understandings of birds' capabilities and their ties to humankind, as well as to other anchors in the natural world. We will take a strong biographical as well as avian approach to understanding key personalities who furthered our understandings of avian science. Instructor: Lewis.

H 135. War, Conquest, and Empires. *9 units (3-0-6); first 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 136. Caltech in the Archives. *9 units (3-0-6); first term.* This class will introduce students to the methods of archival work in the humanities and social sciences. Over the course of the quarter students will receive an introduction to factors surrounding the collection, organization, and use of various types of archives as a

background to several small-scale projects working in an archival collection of their own choosing. The seminar will center around weekly projects and synthetic analytical essays about the archival process and archival discoveries. Students hoping to combine their course work with an archive-based research paper may sign up for a separate independent study and conduct research concurrently, with instructor approval. Instructor: Dykstra.

H 137. Criminals, Outlaws, and Justice in a Thousand Years of Chinese History. *9 units (3-0-6); second term.* This course explores the shifting boundary between discourses of crime and disobedience over the last millennium or so of Chinese history. It offers fictional, philosophical, political, propagandistic, official, and personal writings on crime and those who commit it as a basis for a wide-ranging series of discussions about when breaking the law is good, when breaking the law is bad, and who gets to decide where the line between a criminal and an outlaw should be drawn. Instructor: Dykstra. Not offered 2019–20.

H 138. The Way. *9 units (3-0-6); second term.* This course introduces students to some of the seminal writings on the meaning of life, the essentials of rulership, and the place of the individual in the universe from the history of Chinese thought and philosophy. Students are given selected readings from several schools of thought in Chinese history, with an emphasis on the formative Warring States era (the period of the Hundred Schools of classical Chinese philosophy). Instead of being asked to write expository or argumentative essays, participants in this seminar will be introduced to analyzing and presenting texts using the method of annotation. Exposure to the principles of annotation will provide students with a new approach to analyzing and talking about texts both within a humanistic context and beyond. Not offered 2019–20. Instructor: Dykstra.

H 139. Translation Theory and Practice (Chinese Historical Sources Seminar). *9 units (3-0-6).* For course description, see L 139. Instructor: Dykstra.

H/L 142. Perspectives on History through Russian Literature. *9 units (3-0-6); first term.* The Russian intelligentsia registered the arrival of modern urban society with a highly articulate sensitivity, perhaps because these changes—industrialization, the breakdown of traditional hierarchies and social bonds, the questioning of traditional beliefs—came to Russia so suddenly. This gives their writings a paradigmatic quality; the modern dilemmas that still haunt us are made so eloquently explicit in them that they have served as models for succeeding generations of writers and social critics. This course explores these writings (in English translation) against the background of Russian society, focusing especially on particular

works of Chekhov, Dostoevsky, Goncharov, Tolstoy, and Turgenev.
Instructor: Dennison.

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

H 149. Age of Fracture: America Since 1974. 9 units (3-0-6); *second term*. In this course, we will examine America after Richard Nixon's resignation in 1974, a period that historians have referred to as an age of fracture and social disaggregation. Using fracture as a conceptual framework to investigate American politics and culture in the last quarter of the twentieth century, we'll consider how the recent past has informed present-day American society. Themes of study will include the culture wars, political polarization, globalization, and the growing wealth gap. In addition, we'll investigate the theoretical and methodological challenges of doing recent history. Instructor: Wiggins.

H 150. America in the 1960s. 9 units (3-0-6); *first term*. The course adopts a thematic approach to the "long 1960s," engaging in depth with the political, social, and cultural trends that shaped the decade. Topics include the African American struggle for civil rights, the "urban crisis," Cold War culture, liberalism at high tide, the Vietnam War, sexual liberation, the New Left and counterculture, as well as the rise of the New Right. Throughout, the course interrogates the privileged role given the 1960s in American history, questioning to what extent the decade marked a departure from the American past or a continuation of long-running trends. Instructor: Savage.

H 151. The Long(er) Civil Rights Movement: From Emancipation to Black Lives Matter. 9 units (3-0-6); *third term*. Taking historian Jacqueline Dowd Hall's call to expand the chronology of the civil rights narrative rather generously, this course explores African American freedom struggles over a period bookended by emancipation and the Black Lives Matter movement. Through an analysis of a wide array of historical sources, the course will also examine topics such as Reconstruction, the rise of Jim Crow, the Great Migration, the civil rights movement of the 1950s and 1960s, Northern and Western segregation, and mass incarceration. Instructor: Savage.

H 152. Where Do We Go from Here? Black America in the Post-Civil Rights Era. 9 units (3-0-6); *first term*. This course will examine African American politics, culture, and society in the decades following the passage of landmark civil rights legislation in the 1960s. Topics of discussion will include deindustrialization and the rise of hip hop culture, black feminist and queer thought, debates over welfare and affirmative action, and mass incarceration. Analyzing a variety of political and cultural artifacts as well as cutting-edge

secondary literature, we will investigate various moments in recent African American history to gain insight into changing notions of rights, citizenship, equality, and freedom in American society. Instructor: Wiggins.

HPS/H 160. 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); first term. Instructor: Styles.

HPS/H 162. Social Studies of Science. 9 units (3-0-6). For course description, see History and Philosophy of Science.

HPS/H 166. Historical Perspectives on the Relations between Science and Religion. 9 units (3-0-6). For course description, see History and Philosophy of Science.

HPS/H 167. Experimenting with History/Historic Experiment. 9 units (3-0-6). For course description, see History and Philosophy of Science.

HPS/H 168. History of Electromagnetism and Heat Science. 9 units (3-0-6). For course description, see History and Philosophy of Science.

HPS/H 169. Selected Topics in the History of Science and Technology. 9 units (3-0-6). For course description, see History and Philosophy of Science.

HPS/H 170. History of Light from Antiquity to the 20th Century. 9 units (3-0-6). For course description, see History and Philosophy of Science.

HPS/H 171. History of Mechanics from Galileo through Euler. 9 units (3-0-6). For course description, see History and Philosophy of Science.

HPS/H 172. History of Mathematics: A Global View with Close-ups. 9 units (3-0-6). For course description, see History and Philosophy of Science.

HPS/H 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 180. Forbidden Knowledge. 9 units (3-0-6). For course description, see History and Philosophy of Science.

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 2019–20.

H/HPS/VC 185. Angels and Monsters: Cosmology, Anthropology, and the Ends of the World. 9 units (3-0-6); *second 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. Not offered 2019–20.

H/HPS/VC 186. From Plato to Pluto: Maps, Exploration and Culture from Antiquity to the Present. 9 units (3-0-6); *second term*. This course covers a broad range of topics in the history of maps and exploration from Antiquity to the present. These topics range from the earliest visualizations of earth and space in the Classical world to contemporary techniques in interplanetary navigation. By way of maps, students will explore various ways in which different cultures have conceptualized and navigated earth and space. While maps emulate the world as perceived by the human eye, they, in fact, comprise a set of observations and perceptions of the relationship between bodies in space and time. Thus, students will study maps, and the exploration they enable, as windows to the cultures that have produced them, not only as scientific and technical artifacts to measure and navigate our world. Instructors: Wey-Gomez, Ceva.

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 fed-

erated 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 2019–20.

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 2019–20.

H 189. The Ethics of War. 9 units (3-0-6); third term. We tend to think of violence as a breakdown in social order, but warfare, as an organized form of violence, complicates this perspective. Can waging war and upholding justice go hand in hand? In this seminar, we will explore theories of just war from Classical antiquity through the Middle Ages, paying particular attention to methods of categorizing warfare, women at war, and pacifist critiques. The course will conclude by assessing depictions of medieval warfare in contemporary culture, such as Vikings or Game of Thrones. Readings may include Aristotle, Cicero, Augustine, Thomas Aquinas, medieval handbooks of chivalry, Ælfric of Eynsham, documents from the trial of Joan of Arc, and Thomas More. Not offered 2019–20.

H/L 191. Perspectives on History through German Literature. 9 units (3-0-6); third 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. Not offered 2019–20.

H 192. The Crusades. *9 units (3-0-6); third 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? Instructor: Brown.

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 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 2019–20.

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

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 18. Introduction to the History of Science. *9 units (3-0-6).* For course description, see Humanities.

HPS 98. Reading in History and Philosophy of Science. *9 units (1-0-8).* *Prerequisite: instructor's permission.* An individual program of directed reading in history and philosophy of science, in areas not covered by regular courses. Instructor: Staff.

HPS 102 ab. Senior Research Seminar. *12 units (2-0-10).* Offered in any two consecutive terms, by arrangement with HPS faculty. Under the guidance of an HPS faculty member, students will research and write a focused research paper of 15,000 words (approximately 50 pages). Work in the first term will comprise intensive reading in the relevant literature and/or archival or other primary source research. In the second term, students will draft and revise their paper. Open to seniors in the HPS option and to others by special permission of an HPS faculty member. Instructor: Staff.

HPS 103. Public Lecture Series. *1 unit; first, second, third terms.* Student attend four lectures, featuring speakers from outside Caltech, on topics in the history and philosophy of science. Students may choose from a variety of regularly scheduled HPS lectures, including HPS seminars, Harris lectures, and 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/PI/CS 110. Causation and Explanation. *9 units (3-0-6); third 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 120. Introduction to Philosophy of Science. *9 units (3-0-6); first 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: Sebens.

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 2019–20.

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. Instructor: Sebens.

HPS/PI 124. Philosophy of Space and Time. 9 units (3-0-6); second 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. Instructor: Hubert.

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? Instructor: Hubert.

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. Instructor: Hitchcock. Not offered 2019–20.

HPS/PI 136. Happiness and the Good Life. *9 units (3-0-6); first 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. Instructor: 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 160. 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/PI 165. Selected Topics in Philosophy of Science. 9 units (3-0-6). 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). third term. *Prerequisites: Ph 1 abc, and Ph 2 abc (may be taken concurrently).* 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); third term. *Prerequisites: Ph 1 abc, and Ph 2 abc (may be taken concurrently).* 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. Instructor: Buchwald. Not offered 2019–20.

HPS/H 169. Selected Topics in the History of Science and Technology. 9 units (3-0-6). Instructors: Staff, visiting lecturers.

HPS/H 170. History of Light from Antiquity to the 20th Century. 9 units (3-0-6); second, third terms. Prerequisites: Ph 1 abc, and Ph 2 abc (may be taken concurrently). A study of the experimental, mathematical, and theoretical developments concerning light, from the time of Ptolemy in the 2nd century A.D. to the production of electromagnetic optics in the 20th century. Instructor: Buchwald, J. Not offered 2019–20.

HPS/H 171. History of Mechanics from Galileo through Euler. 9 units (3-0-6). Prerequisites: Ph 1 abc, and Ph 2 abc (may be taken concurrently). 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 2019–20.

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 2019–20.

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 2019–20.

HPS/H 180. Forbidden Knowledge. 9 units (3-0-6); first term. Why does the notion of freedom of knowledge and teaching in science and engineering matter? What kinds of restrictions have been placed on scientists and engineers, their publications and institutions? Who restrained scientific and engineering knowledge of what sorts; for what reasons; and how successfully? These questions will be addressed by exploring the strategies developed by the U.S. research community to protect the international circulation of knowledge after World War II, when scientific freedom and the export of technical data had to be balanced with the needs of national security. Case studies will include the atomic bomb, the semiconductor industry in the 1970s and space technologies, notably rockets/missiles, in the 1990s. The threat to U.S. economics and military security posed by the Soviet Union in the Cold War, and by China today, has transformed the practice of research in university and in industry alike building new walls around the production and circula-

tion of knowledge to affirm national sovereignty that is, all the while, being undermined by the global circulation of trained scientists and engineers. Instructor: Krige.

H/HPS/VC 185. Angels and Monsters: Cosmology, Anthropology, and the Ends of the World. 9 units (3-0-6). For course description, see History.

H/HPS/VC 186. From Plato to Pluto: Maps, Exploration and Culture from Antiquity to the Present. 9 units (3-0-6). For course description, see History.

HUMANITIES

Hum/H 1. American History. 9 units (3-0-6); *first term*. Among the major events, trends, and problems of our country's history are the American Revolution, the framing and development of the Constitution, wars, slavery and emancipation, ethnic and gender relations, immigration, urbanization, westward conquest, economic fluctuations, changes in the sizes and functions of governments, foreign relations, class conflicts, domestic violence, and social and political movements. Although no one course can treat all of these themes, each freshman American history course will deal with two or more of them. How have American historians approached them? What arguments and evidence have scholars offered for their interpretations and how can we choose between them? In a word, what can we know about our heritage? Instructor: Kousser.

Hum/H 2. Which Side Are You On? 20th Century African American History Through Debate. 9 units (3-0-6); *second term*. In this introductory course, we will discuss twentieth-century African American history by examining debates that have defined black politics, culture, and society. With a focus on analyzing primary sources and critiquing secondary literature, we will trace the contours of historical and historiographical debates in African American history and gain an understanding of the diversity of thought and experience among black Americans. Instructor: Wiggins.

Hum/H 3. The United States in the Twentieth Century. 9 units (3-0-6); *first term*. Designed to introduce students to the academic study of history, this course examines key issues and events that shaped the political, social, and cultural history of the United States in the Twentieth Century. Through a wide variety of historical sources—including primary documents, fiction, and music—students will explore issues such as popular culture, immigration and labor, the civil rights movement, political realignment, and American intervention abroad. Instructor: Savage.

Hum/H 5. The History of the Chinese Empire. 9 units (3-0-6); first term. This class will explore several facets of how the concept of empire and its historical formation in China was defined, portrayed, and developed over time. It offers students a chance to reflect on the interaction of event, record, and remembrance as these components combine in the creation and contestation of history. This course will particularly emphasize how the making, writing, and remembering of history responds to the advent of different regimes of legitimacy in order to give students a new perspective on the relationship between action, authorship, and interpretation in history. Instructor: Dykstra.

Hum/H 8 a. Civilization, Science, and Archaeology: Before Greece: The Origins of Civilization in Mesopotamia. 9 units (3-0-6); third term. This course will introduce students to the early development of civilization in Mesopotamia and Egypt from 4000 B.C.E. through 1000 B.C.E. Origins of agriculture and writing, the evolution of the city, and the structures of the Mesopotamian economy and social order will be discussed. Comparison with contemporary developments in Egypt during the Old and Middle Kingdoms may include a reading of Gilgamesh from 3000 B.C.E. and of the Egyptian Tale of Sinuhe. The course concludes with a discussion of life during the late Bronze Age. Focus will be on life as it was lived and experienced by many groups in pre-classical antiquity rather than on kings and dynasties. Instructor: Buchwald. Not offered 2019–20.

Hum/H 8 b. Civilization, Science, and Archaeology: The Development of Science from Babylon through the Renaissance. 9 units (3-0-6); second, third terms. 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. Instructors: Buchwald, J.

Hum/H 8 c. Civilization, Science, and Archaeology: The Nature of Religious Belief in Ancient Egypt, Mesopotamia, and Israel. 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 2019–20.

Hum/H 9 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. Not offered 2019–20.

Hum/H 9 b. European Civilization: Early Modern Europe. *9 units (3-0-6); first, second, third terms.* 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: Hoffman, Wey-Gomez.

Hum/H 9 c. European Civilization: Modern Europe. *9 units (3-0-6); third term.* 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.

Hum/H 10. Medieval Europe: The Problem of Violence. *9 units (3-0-6); second, third terms.* This course will explore how people understood violence in Europe between ca. 500 and ca. 1400 AD. It will focus on the various norms that governed the use of violence in a period when the right of free people to carry and use weapons was considered self-evident. Working through primary sources, students will explore the relationship between violence and vengeance, the law, central authority and public order, religion, emotions, public ritual, and economics. As they go along students will consider whether violence can coexist with or even promote stable, ordered societies, or whether it by definition creates disorder. Instructor: Brown.

Hum/H 11. Love and Death: Using Demography to Study the History of Europe from 1700. *9 units (3-0-6); first, second terms.* Demographic events—births, marriages, deaths—have always been

highly responsive to changes in the local environment. Decisions about when to marry, how many children to have, or what kind of household to live in have always been closely correlated to decisions people take in other areas of their lives and, as a result, can tell us a great deal about the economic, social, and cultural worlds people inhabit. This course examines differences in demographic trends in Europe across space and time, from 1700 to the present, as well as existing explanations for these differences, including political economic factors, social and cultural norms, biology and disease environments. Some topics include: the demographic effects of war, industrialization, and urbanization; changes related to the emergence of reliable contraceptive technologies; changes related to the expansion of economic opportunities for women; the effects of government policies on demographic decisions. Instructor: Dennison.

Hum 15. Special Topics in Humanities. *9 units (3-0-6); offered by announcement.* This course will count as a freshman humanities course in either English, history, philosophy, or visual culture, as announced. It is usually taught by new or visiting faculty. The course may be re-taken once if the second class is offered in a different discipline (from among English, history, philosophy, and visual culture). Limited to 15 students. See registrar's announcement for details. Instructor: Staff.

Hum/H/HPS 18. Introduction to the History of Science. *9 units (3-0-6); second, third terms.* 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/En 20. Greek Epic and Drama. *9 units (3-0-6); first, second terms.* The epic poems attributed to Homer, the Iliad and the Odyssey, and Athenian drama of the fifth and early fourth centuries BCE have been masterpieces of the western literary tradition for thousands of years. We will study one or both epics, tragedies by Aeschylus, Sophocles, and Euripides, and comedies by Aristophanes. Instructor: Pigman.

Hum/En 21. The Marvelous and the Monstrous: Literature at the Boundaries of the Real. 9 units (3-0-6); second, third terms.

Marvels flourish at the boundaries of literary invention, religious belief, and scientific inquiry, challenging assumptions about natural processes and expected outcomes. From Grendel, the monstrous foe of Beowulf, to Satan, Milton's charismatic antihero, this seminar examines the uses of the marvelous in a variety of texts and genres, including Shakespearian drama, medieval romance, and early travel-writing. Readings may include Beowulf, Marie de France, Chaucer, John Mandeville, Shakespeare, Milton. Instructor: Jahner. Not offered 2019–20.

Hum/En 22. Inequality. 9 units (3-0-6); second term.

Throughout the history of Europe, America, and beyond, poets and philosophers have asked hard questions about unequal relationships, whether between kings and subjects, gods and humans, men and women, rich and poor, or machines and people. Our authors take no single point of view; our goal is to analyze sophisticated and often surprising arguments and to enter new cultural worlds. Readings may include Ovid, Milton, Sei Shonagon, Machiavelli, Rousseau, and Alexievich. Instructor: Haugen.

Hum/En 23. Literature and Medicine. 9 units (3-0-6); third term.

The relationship between patients and doctors, the ill and the well, involves a constant exchange of stories. In this course we will look more closely at the relationship between medicine and narrative through a selection of fiction, essays and poems that investigate the interplay between doubt and diagnosis, the idea of the case study, the problem of medical responsibility, and the language of pain and illness. Authors covered may include Sontag, Mantel, Conan Doyle, Freud, Woolf, Dickinson, Ishiguro and Shelley. Instructor: Gilmore. Not offered 2019–20.

Hum/En 24. The Scientific Imagination in English Literature.

9 units (3-0-6); third term. This course considers three periods of major scientific development—the Renaissance, the nineteenth century, and the modern period—to explore the influence new ideas, discoveries, and theories had on the imagination of English writers. We will look at the early modern interplay between magic and science, Romantic and Victorian debates about evolution, and the twentieth-century advent of modern physics as we confront consistent tropes like the mad scientist, the scientist-hero, and the problem of uncertainty. Authors covered may include Shakespeare, Marlowe, Bacon, Shelley, Darwin, Conan Doyle, Stevenson, Auden, McEwan, and Stoppard. Instructor: Gilmore.

Hum/En 25. The Human Animal. 9 units (3-0-6); second term. European literature has long been a testing ground for radical new ideas which have come to shape our basic understanding of what

it means to be a thinking, speaking and perhaps even autonomous human being. The question of what - if anything - makes us different from animals was debated from numerous points of view: including talking dogs, philosophizing women, bestial men, humanlike beasts, and other creatures that defied the conventions of the time. This course explores some of the key literary texts that shaped this debate and pays careful attention to their cultural environments. Selected readings from Cervantes, La Fontaine, Swift, Rousseau, Buffon, Aikin, and Wollstonecraft, among others. Instructor: Holland.

Hum/En 29. Dream Narratives. *9 units (3-0-6); third term.* Dream narratives reveal as much about cultural beliefs and superstitions as they do about techniques of narration and interpretation. This course investigates key developments in the literature on dreams and dream interpretations with examples drawn from the Renaissance through the beginning of the nineteenth century. Selected readings from Boccaccio, Descartes, Calderón, Shakespeare, and Diderot, among others. Instructor: Holland.

Hum/En 33. Modern Metamorphoses. *9 units (3-0-6); second term.* Narratives of metamorphosis have traditionally used their dramatic subject matter—a radical change of form—as a vehicle for social criticism. This course explores the ways in which twentieth-century writers experiment with the concept of metamorphosis to take on the most pressing political and social issues of their day, including slavery, women's rights, and critiques of capitalist excess. Readings to include Kafka, Garnett, Orwell, Tawada, and Erpenbeck. Instructor: Holland. Not offered 2019–20.

Hum/En 35. 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. Not offered 2019–20.

Hum/En 36. 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. Not offered 2019–20.

Hum/En 37. 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. Not offered 2019–20.

Hum/En 38. Telling Time in American Modernism. 9 units (3-0-6); *first term*. This course will explore modern American literature's interest in time. We will identify the narrative methods that modernist texts use to characterize the experience of lived time, or temporality, such as streams of consciousness, non-linear storytelling, and narrative omissions. What challenges do such methods pose to clock time and, more broadly, historical time? Students will learn about key literary movements within American modernism, and they will consider modernist literature's relationships to other genres and media, including music and visual culture. The course will emphasize modernism's engagements with shifting social norms related to race, class, gender, and sexuality during the first half of the twentieth century. Instructor: Sherazi.

Hum/En 39. Contemporary American Fiction. 9 units (3-0-6); *first term*. This course will engage works of contemporary American fiction, with particular attention paid to experimental narrative strategies and their effects, including non-chronological storytelling, metafictionality, and narrative omissions. Notably, the literature we will read is set during and/or in the aftermath of World War II and/or the Vietnam War. How do the novel's central characters understand their roles in American society before, during, and beyond wartime? We will consider the ways in which social movements, including the civil rights and women's liberation movements, informed these works of fiction and how such literature resonates in our current moment. Authors/texts studied will include John Okada's *No-No Boy* (1957), Joan Didion's *Democracy* (1984), and Susan Choi's *American Woman* (2003). Instructor: Sherazi. Not offered 2019–20.

Hum/PI 40. Right and Wrong. 9 units (3-0-6); *first, second terms*. 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 psy-

chological 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. Instructor: Hay

Hum/PI 41. Knowledge and Reality. *9 units (3-0-6); first, third terms.* 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, Hubert.

Hum/PI 43. Meaning in Life. *9 units (3-0-6); first, second terms.* Experiencing one's life as meaningful is important for most people. Yet, what is it for a life to be meaningful? This course explores philosophical inquiries into meaning in life, examining such questions as, How does meaning in life relate to moral, epistemic, aesthetic, and hedonic final values in life? What does meaning in life imply regarding the metaphysics of value? What is the relation between meaning and welfare, achievement, and goal-directedness? What sort of activities, from work to leisure, can be sources of meaning in life? Drawing principally on recent work in analytic philosophy, the course will also examine whether scientific approaches, principally neuroscience and psychology, can illuminate the nature of meaning in life and will examine recent nihilistic challenges to meaning in life. Instructors: Quartz.

Hum/PI 44. Philosophy Through Science Fiction. *9 units (3-0-6); third term.* This course will provide a broad introduction to philosophy using examples from science fiction to make abstract philosophical problems vivid. Topics may include: time travel and the reality of the past and future; teleportation and what makes someone the same person over time; fictional tales of extended deception and Cartesian skepticism; futuristic utopias and the question of what make a life good; the moral status of aliens and animals; intelligent robots and the relation between mind and body; parallel universes and the philosophical foundations of quantum physics. Instructor: Sebens.

Hum/PI 45. Ethics & AI. *9 units (3-0-6); second term.* How do we reconcile the possibilities of modern machine learning with ethical

and moral demands of fairness, accountability and transparency? This course will take a case study based approach to the challenges at the interface of algorithms and human values. By exploring existing debates on algorithmic bias, explainable AI and data ownership, students will be exposed to the relevance of ethical systems of thought to modern social questions. Instructor: Eberhardt.

Hum/VC 49. Consuming Victorian Media. *9 units (3-0-6); first term.* Proliferating communication and entertainment media technologies in 19th-century England vexed the imagined boundaries between humans and machines while catalyzing social anxieties about aesthetics, attention, and distraction. We will explore both “old” (novels, paintings, sculptures) and “new” forms of 19th-century media (telegraphs, magic lanterns, and photography) as we analyze overly stimulating Gothic print media in Jane Austen’s *Northanger Abbey*, Wordsworth’s contempt for popular entertainments in *The Prelude*, and the inversion of imperial consumption in Bram Stoker’s *Dracula*, a novel mediated through characters’ telegrams, diary entries, and phonographic recordings. Authors studied also may include: Dickens, Christina Rossetti, Doyle, Kipling, and Vernon Lee. Instructor: Sullivan.

Hum/VC 50. Introduction to Film. *9 units (3-0-6); third term.* This course examines film as a technology, entertainment medium, and commercial art with an emphasis on American and European contexts. Students will acquire the basic vocabulary and techniques of film analysis, with an emphasis on style and structure, and develop an understanding of the historical development of film as both an art form and an industry from 1895 through the twentieth century. Topics covered include actualities and the birth of narrative film, silent film comedy, German expressionism, the Hollywood star system, Italian neo-realism, and the French New Wave. Instructor: Jurca.

Hum 75. Selected Topics in Humanities. *variable units; offered by announcement.* A course on a specialized topic in some area of the humanities, usually taught by new or visiting faculty. Recent offerings have included courses on film-making, poetry writing, speculative fiction, and the difference between humans and other animals. The course may be re-taken for credit except as noted in the course announcement. Class size is normally limited to 8 - 15 students. See registrar’s announcement for details. Instructors: Staff, visitors.

Hum 80. Frontiers in the Humanities. *1 unit (1-0-0); third term.* Weekly seminar by a member of the Caltech humanities faculty or a visitor to discuss a topic of his or her current research at an introductory level. The course can be used to learn more about different areas of study within the humanities. For those interested in (or who become interested) in pursuing a second option in the humanities,

the course will introduce students to the kinds of research carried out by members of the humanities faculty and help them find faculty advisors. Instructors: Staff.

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

Hum 114 abc. Spanish and Latin American Literature. 9 units (3-0-6). For course description, see L 114 abc.

Hum 119. Selected Topics in Humanities. *variable; offered by announcement.* This is an advanced humanities course on a specialized topic in some area of the humanities. It is usually taught by new or visiting faculty. The course may be re-taken for credit except as noted in the course announcement. Limited to 15 students. See registrar's announcement for details. Instructors: Staff, visitors.

L/Hum 150 a. Japanese Literature in Translation. 9 units (3-0-6). For course description, see Languages.

L/Hum 150 b. Japanese Literature in Translation. 9 units (3-0-6). For course description, see Languages.

L/Hum 152 ab. French Literature in Translation: Classical and Modern. 9 units (3-0-6). 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. Advanced Chinese II: Topics in Chinese Literature. 9 units (3-0-6). For course description, see L 174.

HPS/H 180. Forbidden Knowledge. 9 units (3-0-6); *first term.* For course description, see History and Philosophy of Science.

INFORMATION AND DATA SCIENCES

IDS 9. Introduction to Information and Data Systems Research. 1 unit (1-0-0); *second term.* This course will introduce students to research areas in IDS through weekly overview talks by Caltech faculty and aimed at first-year undergraduates. Others may wish to take the course to gain an understanding of the scope of research in computer science. Graded pass/fail. Not offered 2019–20.

ACM/IDS 101 ab. Methods of Applied Mathematics. 12 units (4-4-4). For course description, see Applied and Computational Mathematics.

ACM/IDS 104. Applied Linear Algebra. 9 units (3-1-5). For course description, see Applied and Computational Mathematics.

CMS/ACM/IDS 107. Linear Analysis with Applications. 12 units (3-3-6). For course description, see Computing and Mathematical Sciences.

CMS/ACM/IDS 113. Mathematical Optimization. 12 units (3-0-9). For course description, see Computing and Mathematical Sciences.

ACM/EE/IDS 116. Introduction to Probability Models. 9 units (3-1-5). For course description, see Applied and Computational Mathematics.

CS/IDS 121. Relational Databases. 9 units (3-0-6). For course description, see Computer Science.

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

EE/Ma/CS/IDS 136. Topics in Information Theory. 9 units (3-0-6). For course description, see Electrical Engineering.

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

CS/IDS 142. Distributed Computing. 9 units (3-0-6). For course description, see Computer Science.

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

Ma/ACM/IDS 140 ab. Probability. 9 units (3-0-6); second, third terms. For course description, see Mathematics.

CMS/CS/EE/IDS 144. Networks: Structure & Economics. 12 units (3-4-5). For course description, see Computing and Mathematical Sciences.

CS/IDS 150 ab. Probability and Algorithms. 9 units (3-0-6). For course description, see Computer Science.

CS/IDS 153. Current Topics in Theoretical Computer Science. 9 units (3-0-6). For course description, see Computer Science.

ACM/IDS 154. Inverse Problems and Data Assimilation. 9 units (3-0-6). For course description, see Applied and Computational Mathematics.

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

IDS/ACM/CS 157. Statistical Inference. 9 units (3-2-4); third term. Prerequisites: ACM/EE/IDS 116, Ma 3. Statistical Inference is a branch of mathematical engineering that studies ways of extracting reliable information from limited data for learning, prediction, and decision making in the presence of uncertainty. This is an introductory course on statistical inference. The main goals are: develop statistical thinking and intuitive feel for the subject; introduce the most fundamental ideas, concepts, and methods of statistical inference; and explain how and why they work, and when they don't. Topics covered include summarizing data, fundamentals of survey sampling, statistical functionals, jackknife, bootstrap, methods of moments and maximum likelihood, hypothesis testing, p-values, the Wald, Student's t-, permutation, and likelihood ratio tests, multiple testing, scatterplots, simple linear regression, ordinary least squares, interval estimation, prediction, graphical residual analysis. Instructor: Zuev.

IDS/ACM/CS 158. Fundamentals of Statistical Learning. 9 units (3-3-3); third term. Prerequisites: Ma 3 or ACM/EE/IDS 116, IDS/ACM/CS 157. The main goal of the course is to provide an introduction to the central concepts and core methods of statistical learning, an interdisciplinary field at the intersection of statistics, machine learning, information and data sciences. The course focuses on the mathematics and statistics of methods developed for learning from data. Students will learn what methods for statistical learning exist, how and why they work (not just what tasks they solve and in what built-in functions they are implemented), and when they are expected to perform poorly. The course is oriented for upper level undergraduate students in IDS, ACM, and CS and graduate students from other disciplines who have sufficient background in probability and statistics. The course can be viewed as a statistical analog of CMS/CS/CNS/EE/IDS 155. Topics covered include supervised and unsupervised learning, regression and classification problems, linear regression, subset selection, shrinkage methods, logistic regression, linear discriminant analysis, resampling techniques, tree-based methods, support-vector machines, and clustering methods. Instructor: Zuev.

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

EE/CS/IDS 160. Fundamentals of Information Transmission and Storage. 9 units (3-0-6). For course description, see Electrical Engineering.

CS/IDS 162. Data, Algorithms and Society. 9 units (3-0-6). For course description, see Computer Science.

CS/CNS/EE/IDS 165. Foundations of Machine Learning and Statistical Inference. 12 units (3-3-6). For course description, see Computer Science.

EE/CS/IDS 167. Introduction to Data Compression and Storage. 9 units (3-0-6). For course description, see Electrical Engineering.

ACM/EE/IDS 170. Mathematics of Signal Processing. 12 units (3-0-9). For course description, see Applied and Computational Mathematics.

CS/IDS 178. Numerical Algorithms and their Implementation. 9 units (3-3-3). For course description, see Computer Science.

IDS 197. Undergraduate Reading in the Information and Data Sciences. *Units are assigned in accordance with work accomplished; first, second, third terms. Prerequisites: Consent of supervisor is required before registering.* Supervised reading in the information and data sciences 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.

IDS 198. Undergraduate Projects in Information and Data Sciences. *Units are assigned in accordance with work accomplished; first, second, third terms. Prerequisites: Consent of supervisor is required before registering.* Supervised research in the information and data sciences. The topic must be approved by the project supervisor and a formal report must be presented upon completion of the research. Graded pass/fail. Instructor: Staff.

IDS 199. Undergraduate thesis in the Information and Data Sciences. 9 units (1-0-8); *first, second, third terms. Prerequisites: 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 faculty member and approved by the option representative. Projects must include significant design effort and a written Report is required. Open only to upperclass students. Not offered on a pass/fail basis. Instructor: Staff.

ACM/IDS 204. Topics in Linear Algebra and Convexity. 12 units (3-0-9). For course description, see Applied and Computational Mathematics.

ACM/IDS 213. Topics in Optimization. 9 units (3-0-6). For course description, see Applied and Computational Mathematics.

ACM/IDS 216. Markov Chains, Discrete Stochastic Processes and Applications. 9 units (3-0-6). For course description, see Applied and Computational Mathematics.

ACM/EE/IDS 217. Advanced Topics in Stochastic Analysis. 9 units (3-0-6). For course description, see Applied and Computational Mathematics.

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. Not offered 2019–20. Instructor: Bruck.

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 305–306 for complete details.

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 2019–20.

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: Merrill, Orcel.

L 104. French Cinema. 9 units (3-0-6); first term; Offered concurrently with VC 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 VC 104, which satisfies the advanced humanities requirement. Instructor: Orcel. Not offered 2019–20.

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. Instructor: Orcel. Not offered 2019–20.

L 106 abc. Elementary Japanese. 9 units (4-0-5); 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: Fujio.

L 107 abc. Intermediate Japanese. 9 units (3-0-6); first, second, third terms. Prerequisites: L 106 abc or equivalent. Continued instruction and practice in conversation, building up vocabulary, and understanding complex sentence patterns. The emphasis, however, will be on developing reading skills. Recognition of approximately 1,000 characters. Instructor: Hirai.

L 108 abc. Advanced Japanese. 9 units (3-0-6); first, second terms. Prerequisites: 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. Instructor: Hirai.

L/VC 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 Melies and the Lumiere brothers and working through surrealism and impressionism, 1930s poetic realism, the Occupation, the New Wave, the Cinema du look, and the contemporary cinema. The class will teach students to look at film as a medium with its own techniques and formal principles. Conducted in English. Instructor: Orcel.

L 110 abc. Elementary Spanish. 9 units (3-0-6); first, second, third terms. Grammar fundamentals and their use in understanding, speaking, reading, and writing Spanish. Exclusively for students with no previous knowledge of Spanish. Instructors: Arjona, Garcia.

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: 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. Instructor: 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 139. Translation Theory and Practice (Chinese Historical Sources Seminar). 9 units (3-0-6); first term. This seminar will introduce students to the problems and practices of historical translation for academic purposes, with a focus on primary materials from Chinese history. Students will take responsibility for an individual translation project, participate in seminar discussions and collaborative projects to improve the translations being made, and discuss the philosophical and methodological questions at the heart of the practice of translation. Advanced proficiency in written Chinese is required. Students who write analyses (4,000 words) of the sources being translated may enroll in this class as H 139, which satisfies the advanced humanities credit. Instructor: Dykstra. Not offered 2019–20.

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 2019–20.

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

L/Hum 150 a. Japanese Literature in Translation. 9 units (3-0-6); third term. Read and examine the selected classical Japanese literature and its traditions from 7th to 11th century from the perspectives of women, anti-heroes, and religions. A comparative analysis is applied to many genres such as oral traditions, performing arts, films, picture scrolls, comics, and anime to understand

how Japanese think, and how Shinto and Buddhism have formed their ways of life, ethics, and concepts of life and death. Read selected portions of “The Kojiki”, “Manyoshu”, “The Tale of Ise”, “The tale of the Bamboo-Cutter” (The Tale of the Moon Princess), and “The Tale of Genji.” Instructor: Hirai.

L/Hum 150 b. Japanese Literature in Translation. *9 units (3-0-6); third term.* Read and examine the selected Medieval to pre-modern Japanese literature and its traditions from 11th to 18th century from the perspectives of women, anti-heroes, and religions. A comparative analysis is applied to many genres such as oral traditions, performing arts, films, picture scrolls, comics, and anime to understand how Japanese think, and how Shinto, Buddhism, Neo-Confucianism, as well as the social systems, have formed their ways of life, ethics, and concepts of life and death. Read “The Princess Who Loved Insects” from “The Tsutsumi-Chunagon Monogatari”, selected chapters of “The Tale of The Heike”, “The Konjyaku Monogatari”, and “Otogizoshi”. Also read “The Double Suicide at Sonezaki” and “The Double Suicide at Amijima.” Instructor: Hirai. Not offered 2019–20.

L/Hum 152 ab. French Literature in Translation: Classical and Modern. *9 units (3-0-6); third term.* French classical literature of the 17th and 18th centuries; third term: reading and discussion of works by selected 19th- and 20th-century authors. The approach is both historical and critical. Conducted in English, but students may read the French originals. Film versions of the texts studied may be included. Instructor: Merrill.

L/VC 153. Refugees and Migrants’ Visual and Textual Representations. *9 units (3-0-6); second term.* This course focuses on the refugees and migrants’ images in documentaries, narrative films, graphic novels, fictional texts, poetic works, and autobiographical narratives. It investigates how these representations participate in the development and strengthening of political discourse. Works by authors such as Hannah Arendt, Antje Ellermann, Achille Mbembe, Martin A. Schain, and Sasha Polakow-Suransky will provide some context to our analysis. Topics discussed in class include the historical and economic relationships of Europe with the refugees and migrants’ countries of origin, the rise of anti-immigrant politics and its significance for the future of the European Union, but also its impact on social peace, in France in particular. This course is taught in English. Instructor: Orcel.

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. Not offered 2019–20.

L 167. Latin Literature. 9 units (3-0-6); second term. *Prerequisites:* 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. 9 units (3-0-6); 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 (3-0-6); 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. 9 units (3-0-6); 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. 9 units (3-0-6); 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. Advanced Chinese II: 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. Instructor: 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. Law and Economics. 9 units (3-0-6); third term. This is a law and economics course that studies the economic rationale for different legal principles, using environmental regulations as leading examples. In situations where free markets produce inefficient outcomes, we wish to understand what types of constraints a government can impose on markets so as to restore efficiency. Topics we will cover include resolution of externalities via market and non-market solutions, problems of the commons and anti-commons, and contracting under incomplete information. Instructor: Schenone.

PI/Law 99. Causation and Responsibility. 9 units (3-0-6). For course description, see Philosophy.

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.

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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 mate-

rials 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: Hofmann.

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 (1-0-0); first, second, third terms. A seminar course designed to introduce advanced undergraduates and graduate students to modern research in materials science. Instructors: Bernardi, Faber, Fultz.

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, defects, thermodynamics, phase equilibria, microstructure, and properties are described. Instructor: 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, architecture, defects, and mechanical properties. Elastic, inelastic, and plastic properties of crystalline and amorphous materials. Relations between stress and strains for different types of materials. Introduction to dislocation theory, motion and forces on dislocations, strengthening mechanisms in crystalline solids. Nanomaterials: properties, fabrication, and mechanics. Architected solids: fabrication, deformation, failure, and energy absorption. Biomaterials: mechanical properties of composites, multi-scale microstructure,

biological vs. synthetic, shear lag model. Fracture in brittle solids and linear elastic fracture mechanics. Instructor: Greer.

MS 121. Laboratory Research Methods in Materials Science.

9 units (1-4-4); second term. Prerequisites: MS 115 or graduate standing. Introduction to experimental methods and approaches for the analysis of structure, dynamics, and properties of materials. Staff members with expertise in various areas including mechanical testing, calorimetry, X-ray diffraction, scanning and transmission electron microscopy, solid state NMR and electrochemistry will introduce and supervise experiments in their specialty. As the situation permits, students are given a choice in selecting experiments. Instructor: Ahn.

MS/Aph 122. Diffraction, Imaging, and Structure. 9 units (0-4-5); first term. 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. Instructor: Ahn.

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: Staff. Not offered 2019–20.

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. Instructor: 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. Instructor: Fultz.

MS 133. Kinetic Processes in Materials. 9 units (3-0-6); third term. *Prerequisite:* APh 105 b or ChE/Ch 164, or instructor's permission. Kinetic master equation, uncorrelated and correlated random walk, diffusion. Mechanisms of diffusion and atom transport in solids, liquids, and gases. Coarsening of microstructures. Nonequilibrium processing of materials. Instructors: Greer/Kornfield.

MS 141. Introduction to Computational Methods for Science and Engineering. 9 units (3-0-6); third term. *Prerequisites:* graduate standing or instructor's permission. An introduction to basic methods and code development tools for scientific computing in the Python language, including coding and visualization. Topics include: introduction to Python and its packages Matplotlib, Numpy and SciPy. Numerical precision and sources of error. Root-finding and optimization. Numerical differentiation and integration. Discrete Fourier transforms. Numerical methods for ordinary differential equations. Finite-difference methods for partial differential equations. Introduction to numerical methods for solving linear systems and eigenvalue problems. If time permits: selected topics on data analysis with NumPy, Pandas and Matplotlib. Students will develop numerical calculations in the homework and in a final project. Instructor: Bernardi.

MS 142. Application of Diffraction Techniques in Materials Science. 9 units (2-3-4); second term. *Prerequisite:* Instructor's permission. Applications of X-ray and neutron diffraction methods to the structural characterization of materials. Emphasis is on the analysis of polycrystalline materials but some discussion of single crystal methods is also presented. Techniques include quantitative phase analysis, crystalline size measurement, lattice parameter refinement, internal stress measurement, quantification of preferred orientation (texture) in materials, Rietveld refinement, and determination of structural features from small angle scattering. Homework assignments will focus on analysis of diffraction data. Samples of interest to students for their thesis research may be examined where appropriate. Not offered 2019–20.

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 2019–20.

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. Instructor: Faber.

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.

APh/MS 256. Computational Solid State Physics and Materials Science. 9 units (3-3-3); third term. For course description, see Applied Physics.

ME/MS 260. Micromechanics. 9 units (3-0-6). 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: Ramakrishnan, Gekhtman, Kechris, Makarov, Flach, Ni.

Ma 1 d. Series. 4 units (2-0-2); second term only. Prerequisites: 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: Rains.

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: Wang, Frank.

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 horse-shoe map. Instructor: Parikh.

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. Instructors: Flach, Campbell, Mantovan.

Ma/CS 6/106 abc. Introduction to Discrete Mathematics. 9 units (3-0-6); *first, second, third terms. Prerequisites: 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: Conlon, Shikhelman, Kechris.

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 $ax + by = c$ and $a^2 - db^2 = \pm 1$, constructible numbers, composition of binary quadratic forms, and congruences. Instructor: Xu.

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: Rains.

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: Flach.

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: Ni.

FS/Ma 12. Freshman Seminar: The Mathematics of Enzyme Kinetics. 6 units (2-0-4); third term. For course description, see Freshman Seminars.

Ma 13. Problem Solving in Vector Calculus. 2 units (2-0-0); second term. Prerequisites: Concurrent registration in Ph 1b. A two-hour per week, hands-on class for those students enrolled in Ph 1b needing extra practice with problem solving in vector calculus. Instructor: Rains.

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: Rains.

Ma 20. Frontiers in Mathematics. 1 unit (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. Instructor: Flach.

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 97. Research in Mathematics. *Units to be arranged in accordance with work accomplished.* This course is designed to allow students to continue or expand summer research projects and to work on new projects. Students registering for more than 6 units of Ma 97 must submit a brief (no more than 3 pages) written report outlining the work completed to the undergraduate option rep at the end of the term. Approval from the research supervisor and student's advisor must be granted prior to registration. Graded pass/fail.

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 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: Lazebnik, Durcik, Makarov.

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: Markovic, Gekhtman, Chen.

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 dis-

tributions 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: Angelopoulos, Rains, Durcik.

Ma 111 abc. Topics in Analysis. 9 units (3-0-6); first, second, third terms. Prerequisites: 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, Painleve transcendents and/or elliptic analogues. Instructors: Cuenca, Radzivil, Lazebnik.

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 2019–20.

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 Godel Completeness Theorem and the Completeness Theorem. Definability, elementary equivalence, complete theories, categoricity. The Skolem-Lowenheim Theorems. The back and forth method and Ehrenfeucht-Fraisse games. Fraisse 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: Panagiotopolous.

Ma/CS 117 abc. Computability Theory. 9 units (3-0-6); first, second, third terms. *Prerequisite:* Ma 5 or equivalency, 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 2019–20.

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 2019–20.

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: Ramakrishnan, Zhu, Graber.

Ma 121 ab. Combinatorial Analysis. 9 units (3-0-6); second, third terms. *Prerequisite:* Ma 5. A survey of modern combinatorial mathematics, starting with an introduction to graph theory and extremal problems. Flows in networks with combinatorial applications. Counting, recursion, and generating functions. Theory of partitions. $(0, 1)$ -matrices. Partially ordered sets. Latin squares, finite geometries, combinatorial designs, and codes. Algebraic graph theory, graph embedding, and coloring. Instructors: Tyomkyn, Conlon.

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 2019–20.

Ma 124. Elliptic Curves. 9 units (3-0-6); second 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 2019–20.

Ma 125. Algebraic Curves. 9 units (3-0-6); third term. *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 2019–20.

EE/Ma/CS 126 ab. Information Theory. 9 units (3-0-6); first, second terms. For course description, see Electrical Engineering.

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

Ma 128. Homological Algebra. 9 units (3-0-6); second term. *Prerequisites:* Math 120 abc or instructor's permission. This course introduces standard concepts and techniques in homological algebra. Topics will include Abelian and additive categories; Chain complexes, homotopies and the homotopy category; Derived functors; Yoneda extension and its ring structure; Homological dimension and Koszul complex; Spectral sequences; Triangulated categories, and the derived category. Instructor: Zhu.

Ma 130 abc. Algebraic Geometry. 9 units (3-0-6); first, second, third terms. *Prerequisite:* Ma 120 (or Ma 5 plus additional reading). Plane curves, rational functions, affine and projective varieties, products, local properties, birational maps, divisors, differentials, intersection numbers, schemes, sheaves, general varieties, vector bundles, coherent sheaves, curves and surfaces. Instructors: Kivinen, Xu, Campbell.

Ma 132 abc. Topics in Algebraic Geometry. 9 units (3-0-6). *Prerequisites:* Ma 130 or instructor's permission. This course will cover advanced topics in algebraic geometry that will vary from year to year. Topics will be listed on the math option website prior to the

start of classes. Previous topics have included geometric invariant theory, moduli of curves, logarithmic geometry, Hodge theory, and toric varieties. This course can be repeated for credit. Not offered 2019-20.

Ma 135 ab. Arithmetic Geometry. 9 units (3-0-6); first term.

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 2019-20.

EE/Ma/CS/IDS 136. Topics in Information Theory. 9 units (3-0-6).

For course description, see Electrical Engineering.

Ma/ACM/IDS 140 ab. Probability. 9 units (3-0-6); second, third

terms. *Prerequisites:* For 140 a, Ma 108 b is strongly recommended. Overview of measure theory. Random walks and the Strong law of large numbers via the theory of martingales and Markov chains. Characteristic functions and the central limit theorem. Poisson process and Brownian motion. Topics in statistics. Instructor: Tamuz, Quimet.

Ma/ACM 142. Ordinary and Partial Differential Equations. 9 units

(3-0-6); third term. *Prerequisite:* Ma 108; Ma 109 is desirable. The mathematical theory of ordinary and partial differential equations, including a discussion of elliptic regularity, maximal principles, solvability of equations. The method of characteristics. Instructor: Isett.

Ma 145 abc. Topics in Representation Theory. 9 units (3-0-

6); second, third terms. *Prerequisites:* Ma 5. This course will discuss the study of representations of a group (or related algebra) by linear transformations of a vector space. Topics will vary from year to year, and may include modular representation theory (representations of finite groups in finite characteristic), complex representations of specific families of groups (esp. the symmetric group) and unitary representations (and structure theory) of compact groups. Part a not offered in 2019-20. Instructors: Kivinen, Cuenca.

Ma 147 abc. Dynamical Systems. 9 units (3-0-6); first, second

terms. *Prerequisites:* Ma 108, Ma 109, or equivalent. First term: real dynamics and ergodic theory. Second term: Hamiltonian dynamics. Third term: complex dynamics. Part c not offered in 2019-20. Instructors: Radziwill, Lazebnik.

Ma 148 ab. Topics in Mathematical Physics. 9 units (3-0-6); second and third terms. This course covers a range of topics in math-

ematical 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. Geometric theory of quantum information and quantum entanglement based on information geometry and entropy. Instructors: Parikh, Makarov.

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: Markovic, Ni, Chen.

Ma 157 abc. 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. Part c not offered in 2019–20. Instructor: Smillie.

Ma 160 abc. Number Theory. 9 units (3-0-6); first, second terms. Prerequisites: 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. Part c not offered in 2019–20. Instructors: Burungale, Campbell.

Ma 162 ab. Topics in Number Theory. 9 units (3-0-6); first, second term. Prerequisite: Ma 160. The course will discuss in detail some advanced topics in number theory, selected from the following: Galois representations, elliptic curves, modular forms, L -functions, special values, automorphic representations, p -adic theories, theta functions, regulators. Instructor: Frank, Burungale.

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. Instructors: Chen, Kechris, Smillie, Zhu, Durcik, Shikhelman, Angelopoulos, Frank, Wang, Tyomkyn, Xu, Isett, Demirel-Frank.

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 10. Thinking Like an Engineer. 1 unit; *first term.* A series of weekly seminars by practicing engineers in industry and academia to introduce students to principles and techniques useful for Mechanical Engineering. The course can be used to learn more about the different areas of study within mechanical engineering. Topics will be presented at an informal, introductory level. Required for ME undergraduates. Graded pass/fail. Instructor: Andrade.

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; momen-

tum and heat transfer including boundary layers with applications to internal and external flows. Not offered on a pass/fail basis. Instructors: Hunt, Blanquart.

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, Daraio, Asimaki.

ME 13/113. 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. 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 (CAD) 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 manual 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. Instructor: Van Deusen.

ME 14. Design and Fabrication. 9 units (3-5-1); third term. Prerequisites: ME 12ab, ME 13. Enrollment is limited and is 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 23/123. CNC Machining. 4 units (0-4-0); third, summer terms. Prerequisites: ME 13/113. Enrollment is limited and is based on responses to a questionnaire available in the Registrar's office. Introduction to computer numerical control machining. Students will learn to create Gcode and Mcode using Computer-Aided Manufacturing (CAM) software; they will be instructed on how to safely prepare and operate the machine's functions; and will be taught how

to implement programmed data into several different types of CNC equipment. The class will cover the parts and terminology of the equipment, fixturing materials, setting workpiece, and tool offsets. Weekly assignments will include the use of CAM software, machine operation demonstrations, and machining projects. Instructor: Staff.

ME 40. Dimensional and Data Analyses in Engineering. 9 units (3-0-6); first term. Prerequisites: Ma 1 abc. The first part of this course covers the application of symmetry and dimensional homogeneity (Buckingham Pi theorem) to engineering analysis of systems. The important role of dimensional analysis in developing empirical theories, designing experiments and computer models, and analyzing data are stressed. The second part of the course focuses on quantitative data analysis including linear regression, least-squares, principle components, Fourier analysis, and Bayesian methods. The underlying theory is briefly covered, but the focus is on application to real-world problems encountered by mechanical engineers. Applications to uncertainty analysis and quantification are discussed. Homework will include implementation of techniques in Matlab. First offered 2020-21. Instructor: Colonius.

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 ACM 11. Two-quarter course sequence covers the general theory and methods of computational fluid dynamics (CFD) and finite element analysis (FEA) with experimental laboratory methods applied to complementary engineering problems in solid, structural, and fluid mechanics. Computational procedures are discussed and applied to the analysis of steady-state, transient, and dynamic problems using a commercial software. CFD and FEA topics covered include meshing, types of elements, steady and unsteady solvers, inviscid and viscous flow, internal and external flow, drag and lift, static and dynamic mechanical loading, elastic and plastic behavior, and vibrational (modal) analysis. Fluid mechanics laboratory experiments introduce students to the operation of a water tunnel combined with laser particle image velocimetry (PIV) for quantified flow field visualization of velocity and vorticity. Solid mechanics experiments introduce students to the operation of a mechanical (axial/torsional) load frame combined with digital image correlation (DIC) and strain gage transducers for quantification and full field visualization of displacement and strain. Technical writing skills are emphasized through the generation of detailed full-length lab reports using a scientific journal format. Instructor: Mello.

ME 72 ab. Engineering Design Laboratory. 9 units (3-4-2) first term; (1-8-0) second term. Prerequisites: ME 14. 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 EAS option. Not offered on a pass/fail basis. Instructors: Mello, Van Deusen.

CS/EE/ME 75 abc. 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 and third terms. 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: Minnich.

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

ME/EE/EST 109. Energy Technology and Policy. 9 units (3-0-6); first term. Prerequisites: Ph 1 abc, Ch 1 ab and Ma 1 abc. Energy technologies and the impact of government policy. Fossil fuels, nuclear power, and renewables for electricity production and transportation. Resource models and climate change policies. New and emerging technologies. Instructor: Blanquart.

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. Not offered 2019–20.

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

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); second, third 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. Not offered 2019–20.

Ae/ME 120 ab. Combustion Fundamentals. 9 units (3-0-6). For course description, see Aerospace.

ME/CS/EE 129. Experimental Robotics. 9 units (3-6-0); first term. This course covers the foundations of experimental realization on robotic systems. This includes software infrastructures, e.g., robotic operating systems (ROS), sensor integration, and implementation on hardware platforms. The ideas developed will be integrated onto robotic systems and tested experimentally in the context of class projects. Instructor: Staff.

ME/CS/EE 133 abc. Robotics. 9 units (3-3-3); first, second, third terms. Prerequisites: ME/CS/EE 129, may be taken concurrently, or with permission of instructor. 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 dexterous manipulation using multifingered hands, and advanced obstacle avoidance and motion planning algorithms. Additional topics include robotics research in the area of autonomous navigation and vision. Including 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 2019–20.

ME/CS/EE 134. Robotic Systems. 9 units (3-6-0); second term. *Prerequisites:* ME/CS/EE 129, may be taken concurrently, or with permission of instructor. This course covers the basics of robotic systems at the intersection of computer vision, machine learning and control. It includes selected topics from each of these domains, and their integration points. The lectures will be accompanied by a project that will integrate these ideas on hardware, including building a custom robotic, with the end result being a final demonstration of the concepts studied in the course. Instructor: Staff.

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); third 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. Not offered 2019–20.

AM/ME 165. Finite 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. Not offered 2019–20.

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); first, third terms. The faculty will prepare courses on advanced topics to meet the needs of graduate students. Instructor: Minnich.

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 2019–20.

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 ab. Computational Solid Mechanics. 9 units (3-5-1). 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. 9 units (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/Ge 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.

AM/CE/ME 252. Linear and Nonlinear Waves in Structured Media. 9 units (2-1-6). For course description, see Applied Mechanics.

ME/MS 260. Micromechanics. 9 units (3-0-6); third term. 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 2019–20.

Ae/AM/CE/ME/Ge 265 ab. Static and Dynamic Failure of Brittle Solids and Interfaces, from the Micro to the Mega. 9 units; (3-0-6). For course description, see Aerospace.

ME/Ge/Ae 266 ab. Dynamic Fracture and Frictional Faulting. 9 units (3-0-6); third term. 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. Instructor: Lapusta.

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. Instructors: Gao, Tai and Wang.

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: An overview of the physiology of a system followed by examples of current clinical medical challenges and research highlighting diagnostic and therapeutic modalities. The final three 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.

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

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

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

EE/CS/MedE 125. Digital Electronics and Design with FPGAs and VHDL. 9 units (3-6-0). For course description, see Electrical Engineering.

MedE/EE/BE 168 abc. Biomedical Optics: Principles and Imaging. 9 units (4-0-5) each; parts a and b are taught in second and third terms in odd academic years starting 2019-20 and part c is taught in second term in even academic years starting 2020-21. Prerequisites: instructor's permission. Part a covers the principles of optical photon transport in biological tissue. Topics include a brief introduction to biomedical optics, single-scatterer theories, Monte Carlo modeling of photon transport, convolution for broad-beam responses, radiative transfer equation and diffusion theory, hybrid Monte Carlo method and diffusion theory, and sensing of optical properties and spectroscopy, (absorption, elastic scattering, Raman scattering, and fluorescence). Part b covers established optical imaging technologies. Topics include ballistic imaging (confocal microscopy, two-photon microscopy, super-resolution microscopy, etc.), optical coherence tomography, Mueller optical coherence tomography, and diffuse optical tomography. Part c covers emerging optical imaging technologies. Topics include photoacoustic tomography, ultrasound-modulated optical tomography, optical time reversal (wavefront shaping/engineering), and ultrafast imaging. Instructor: Wang.

EE/CS/MedE 175. Digital Circuits Analysis and Design with Complete VHDL and RTL Approach. 9 units (3-6-0). For course description, see Electrical Engineering.

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

EE/MedE 187. VLSI and ULSI Technology. 9 units (3-0-6). 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. 189a, 12 units (3-6-3) offered both first and third terms. 189b, 9 units (0-9-0) offered only third term. 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 201 ab. 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 and Gao.

MedE 202. Sensors in Medicine. 9 units (3-0-6); second term. *Prerequisites: None.* Sensors play a very important role in all aspect of modern life. This course is an essential introduction to a variety of physical, chemical and biological sensors that are used in medicine and healthcare. The fundamental recognition mechanisms, transduction principles and materials considerations for designing powerful sensing and biosensing devices will be covered. We will also discuss the development of emerging electronic-skin, wearable and soft electronics toward personalized health monitoring. Participants in the course will develop proposals for novel sensing technologies to address the current medical needs. Instructor: Gao.

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. These technologies have been originally and mainly developed for space exploration. Spinoff applications to medicine have been explored and proven with various degrees of success and maturity. This class introduces these topics, the basics of the technologies, their intended original space applications, and the medical applications. Topics include but are not limited to multimodal imaging, UV/Visible/NIR imaging, imaging spectrometry, sensors, robotics, and navigation. Graded pass/fail. Instructor: Nikzad.

MedE/BE/Ae 243. Physiological Mechanics. 9 units (3-0-6); second term. Prerequisites: 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. Low and High Reynolds number locomotion. Instructor: TBD/

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 51. 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 55. The Great Orchestras: Their History, Conductors and Repertoire. 9 units (3-0-6); third term. This survey course will trace the symphony orchestra from its origins in the mid eighteenth century to the present day. Special emphasis will be given to the great civic orchestras of the nineteenth and twentieth centuries, their conductors, and core orchestral repertoire. Making use of historic audio and video recordings from the twentieth century, along with more recent documentary recordings, students will be exposed to the cultural history of modern Europe and America through the medium of classical music. Instructor: Neenan.

Mu 56. Jazz History. 9 units (3-0-6); second term. This course will examine the history of jazz in America from its roots in the unique confluence of racial and ethnic groups in New Orleans around 1900

to the present. The lives and music of major figures such as Robert Johnson, Jelly Roll Morton, Louis Armstrong, Benny Goodman, Duke Ellington, Count Basie, Charlie Parker, Dizzy Gillespie, Thelonius Monk, Miles Davis and others will be explored. Instructor: Neenan.

Mu 57. 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. Not offered 2019–20.

Mu 58. Harmony I. 9 units (3-0-6), *second term.* *Prerequisite:* Mu 57

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. Not offered 2019–20.

Mu 59. Harmony II. 9 units (3-0-6), *third term.* *Prerequisite:* Mu 58 *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. Not offered 2019–20.

Mu 137. History I: Music History to 1750. 9 units (3-0-6); *first term.*

The course traces the history of music from ancient Greece to the time of Bach and Handel. A survey of the contributions by composers such as Machaut, Josquin, and Palestrina will lead to a more in-depth look at the music of Monteverdi, Purcell, Corelli, Vivaldi, and the two most important composers of the high baroque, Bach and Handel. Instructor: Neenan.

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.

NEUROBIOLOGY

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

Bi/CNS/NB 152. Neural Circuits and Physiology of Appetite and Body Homeostasis. 6 units (2-0-4). For course description, see Biology.

Bi/CNS/NB 154. Principles of Neuroscience. 9 units (3-0-6). For course description, see Biology.

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

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

PI/CNS/NB/Bi/Psy 161. Consciousness. 9 units (3-0-6). For course description, see Philosophy.

Bi/CNS/NB 162. Cellular and Systems Neuroscience Laboratory. 12 units (2-4-6). For course description, see Biology.

NB/Bi/CNS 163. The Biological Basis of Neural Disorders. 6 (3-0-3); second term. *Prerequisites:* Bi/CNS/NB/Psy 150 or instructor's permission. The neuroscience of psychiatric, neurological, and neurodegenerative disorders and of substance abuse, in humans and in animal models. Students master the biological principles including genetics, cell biology, biochemistry, physiology, and circuits. Topics are taught at the research level and include classical and emerging therapeutic approaches and diagnostic strategies. Instructors: Lester, Lois. Given in alternate years; offered 2019–20.

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

CNS/Bi/Psy/NB 176. Cognition. 9 units (4-0-5); third term. For course description, see Computation and Neural Systems.

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 units (2-0-4). For course description, see Biology.

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

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

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). For course description, see Biology.

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

Bi/CNS/NB 250 c. 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). For course description, see Computation and Neural Systems.

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

PERFORMING AND VISUAL ARTS

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.

PVA 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.

PVA 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. Section 2: Piano four-hands. Section 3: Guitar ensemble. Instructors: Jasper White, Ward, Elgart.

PVA 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: Price.

PVA 33 abc. Wind Orchestra. *3 units (0-3-0); first, second, third terms.* The Caltech-Occidental Wind Orchestra is comprised of students, faculty, staff, and alumni from Caltech and Occidental College. The ensemble rehearses Thursday nights from 7:30-9:45 pm. and performs three programs per year (one per term) at Ramo Auditorium and Thorne Hall. Repertoire is comprised of traditional and contemporary music encompassing a wide variety of styles, and regularly features renowned guest artists. Open to students of all levels of previous experience. Instructor: Price.

PVA 34 abc. Jazz Band/Jazz Improvisation. *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, with additional opportunity for the study of improvisation. Class meets one evening per week. Instructor: Catlin.

PVA 35 abc. Glee Club. *3 units (0-3-0); first, second, third terms.* Preparation and performance of choral repertoire spanning a range of historical periods and musical styles. Includes occasional collaborative performances with the orchestra. No previous experience required. Three hours a week. Instructor: Sulahian.

PVA 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 cappella 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.

PVA 40 a. Find Your Stories. *3 units (2-0-1); first term.* Through a series of writing exercises, improvisation, and performance/vocal techniques, students will explore/discover/write new narratives for the ever-changing 21st century global landscape. The class culminates in public presentations recorded in front of a live audience. Instructor: Brophy.

PVA 40 b. Moth to the Flame. *3 units (2-0-1); first term.; second term.* This second term emphasizes the relation of the speaker with community. In multiple five minute presentations covering selected topics, students will condense their stories to communicate complex social/scientific narratives and practice how scientists deal with citizen science and democracy in open forums. Lecturers from other Divisions will discuss their own history of public speaking and share their process on how they construct, justify and arrive at their scientific explanations. Instructor: Brophy.

PVA 40 c. Long Form Storytelling. *3 units (2-0-1); first term.; third term.* This final term combines the various narratives compiled over previous terms and weaves them into a long-form storytelling narrative for a live invited audience at the conclusion. Students receive public speaking experience and end the year with a forum to share their process and their science stories with an invited audience. Efforts will be made to coordinate the event with outside opportunities such as existing TedX or Moth events. Instructor: Brophy.

PVA 41 abc. Storytelling for Scientists. *3 units (2-0-1); first, second, third terms.* To be effective leaders and communicators, scientists need to explain/perform their science. Through a series of writing exercises, performance/vocal techniques with new media, students explore/write and perform new narratives for the ever-changing 21st century global landscape. The final class culminates in original stories recorded in front of a live audience. May be repeated for credit. Instructors: Brophy.

PVA 42 abc. Improvisation for Scientists. *3 units (2-0-1); first, second, third terms.* This class is taught sequentially over the academic year and begins with rudimentary improvisation techniques, and continues in the winter/spring with professional improvisation guidance, long form improvisation, and advanced techniques with monthly public performances. Instructors: Brophy.

PVA 61 abc. Silkscreen and Silk Painting. *3 units (0-3-0); first, second, third terms.* Instruction in silkscreening techniques, primar-

ily for T-shirts. Progressive development of silk painting skills for fine art. Instructor: Barry.

PVA 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.

PVA 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.

PHILOSOPHY

Hum/PI 40. Right and Wrong. 9 units (3-0-6). For course description, see Humanities.

Hum/PI 41. Knowledge and Reality. 9 units (3-0-6). For course description, see Humanities.

Hum/PI 43. Meaning In Life. 9 units (3-0-6). For course description, see Humanities.

Hum/PI 44. Philosophy Through Science Fiction. 9 units (3-0-6). For course description, see Humanities.

Hum/PI 45. Ethics & AI. 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); third 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 2019–20.

PI 100. Free Will. *9 units (3-0-6); second 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. Instructor: Hitchcock.

PI 102. Selected Topics in Philosophy. *9 units (3-0-6); offered by announcement. Prerequisite: Hum/PI 40 or Hum/PI 41 or instructor's permission.*

HPS/PI/CS 110. Causation and Explanation. *9 units (3-0-6).* For course description, see History and Philosophy of Science.

HPS/PI 120. Introduction to Philosophy of Science. *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);* 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).* 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 136. Happiness and the Good Life. *9 units (3-0-6).* 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/CNS/NB/Bi/Psy 161. Consciousness. 9 units (3-0-6); *third term*. *Prerequisites:* None, but strongly suggest prior background in philosophy of mind and basic neurobiology (such as Bi150). One of the last great challenges to our understanding of the world concerns conscious experience. What exactly is it? How is it caused or constituted? And how does it connect with the rest of our science? This course will cover philosophy of mind, cognitive psychology, and cognitive neuroscience in a mixture of lectures and in-class discussion. There are no formal pre-requisites, but background in philosophy (equivalent to PI41, PI110) and in neuroscience (equivalent to BI/CNS 150) is strongly recommended and students with such background will be preferentially considered. Limited to 20. Instructors: Eberhardt, Adolphs.

HPS/PI 165. Selected Topics in Philosophy of Science. 9 units (3-0-6). For course description, see History and Philosophy of Science.

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 2019–20.

PHYSICAL EDUCATION

702

PE 1. Student Designed Fitness. 3 units; *first and 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. Instructor: Staff.

PE 2. Healthier Living. 3 units. *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.* 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. *3 units; first term.* Students will learn fundamental principles of sound running training to help with short-term and long-term improvement. The course will cover workout design, running mechanics, injury prevention and other related topics. The course can accommodate a wide range of abilities and experience levels, from beginner to intermediate. Course assessments will include fitness tests to gauge improvement and written work on running-related topics. Instructors: Staff.

PE 6. Core Training, Beginning/Intermediate. *3 units.* 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.* 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; first 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 11. Rollerblading. *3 units.* Students will learn the fundamentals of skating safely. We will focus on getting you rolling, turning and maneuvering and teaching you to master the heel brake stop, safely! You will be able to skate, stop and turn so that you can enjoy skating as part of your aerobic and muscular fitness routine. Basic elements of fitness will be taught and incorporated such as stretching, balance, core strength and other components of general fitness such as heart rate monitoring and conditioning. Field trips may be a part of this course. Bringing your own equipment is recommended but see instructor for assistance, some equipment will be provided. Instructors: Staff.

PE 14. Basketball Skills, Beginning and 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. *3 units.* Beginning fencing includes basic techniques of attack, defense, and counter-offense. Lecture topics include fencing history, strategy, scouting and analysis of opponents, and gamesmanship. 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 activity 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. Frisbee Golf. *3 units; second term.* This course is designed to provide students an opportunity to learn various disc golf shots (driving, mid-range, putting), strategies, rules, and etiquette. Class time will be used practicing on campus and playing the game at various local courses. Students will develop the knowledge and ability to play disc golf confidently on a recreational basis. Instructor: Staff.

PE 28. Flying Saucers. *3 units.* 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 29. Outdoor Lawn Games. *3 units; third term.* Students will participate in 5 specifically chosen strategic games (Inner Tube Water Polo, Dodgeball, Bocce, Corn Hole, Flag Football) and learn basic strategy and rules, fitness and health components as well as learning how to compete in cooperative team games. Course requirements include great attitude, attendance and effort of having fun and trying something new while working on your coordination and general fitness. Instructors: Staff.

PE 30. Golf, Beginning and Intermediate. *3 units; first term.* 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. Instructors: Staff.

PE 31. Indoor/Outdoor Cycling. *3 units; second term.* During this introductory course students will utilize both indoor cycling and outdoor cycling as a tool for fitness and fun. 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 and helmet however equipment will be provided as needed. Please see instructor. Instructors: Staff.

PE 33. Beginning Triathlon Training. *3 units; third 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; third 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 and Intermediate. *3 units; first, second, third terms.* Instruction in all basic swimming strokes, including freestyle, elementary backstroke, racing backstroke, breaststroke, sidestroke, and butterfly. Instructors: Staff.

PE 37. Beginning Kayaking. *3 units.* 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 proficient swimmers or be able to successfully complete an in-water swim test. Instructors: Staff.

PE 38. Water Polo. *3 units; first 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. Instructor: Staff.

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. Instructor: Staff.

PE 48. T'ai-Chi Ch'uan, Beginning and Intermediate. *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. Instructors: 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. *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 course will review all fundamentals with a refinement of winning shots, serves, and daily games. Instructors: Staff.

PE 56. Squash, Beginning, Intermediate, Advanced. *3 units; first 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 and Intermediate. *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. Instructors: 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. 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 and Intermediate. *3 units; second 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. Instructors: Staff.

PE 81. Bouldering. *3 units; first, second, third terms.* 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 85 ab. Intercollegiate Track and Field Teams. *3 units; second, third terms.* Coach: Raphelson.

PE 87 ab. Intercollegiate Swimming and Diving Teams. *3 units; first, second terms.* Coach: Brabson.

PE 89 ab. Intercollegiate Fencing Teams. *3 units; first, second terms.* Coach: Corbit.

PE 90 abc. Intercollegiate Water Polo Teams. *3 units; first, second, third terms.* Coach: Bonafede.

PE 91 ab. Intercollegiate Basketball Teams. *3 units; first, second terms.* Coaches: Eslinger, Reyes.

PE 92. Intercollegiate Soccer Teams. *3 units; first term.* Coaches: Murray, Gould.

PE 93 ab. Intercollegiate Baseball Team. *3 units; second, third terms.* Coach: Whitehead.

PE 95 ab. Intercollegiate Tennis Teams. *3 units; second, third terms.* Coach: Gamble.

PE 97. Intercollegiate Cross-Country Teams. *3 units; first term.* Coach: Raphelson.

PE 99. Intercollegiate Volleyball Team. *3 units; first term.* Coaches: 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: Cheung, Hsieh, Refael, 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. Instructors: Porter, Cheung, Filippone.

Ph 3. Introductory Physics Laboratory. 6 units (0-3-3); first, second, third terms. Prerequisites: Ph 1 a or instructor's permission. Introduction to experimental physics and data analysis, with techniques relevant to all fields that deal in quantitative data. Specific physics topics include ion trapping, harmonic motion, mechanical resonance, and precision interferometry. Broader skills covered include introductions to essential electronic equipment used in modern research labs, basic digital data acquisition and analysis, statistical interpretation of quantitative data, professional record keeping and documentation of experimental research, and an introduction to the Mathematica programming language. 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). For course description, see Freshman Seminar. Not offered 2019–20.

Ph 5. Analog Electronics for Physicists. 9 units (0-5-4); first term. Prerequisites: Ph1abc, Ma1abc, Ma2 taken concurrently. A fast-paced laboratory course covering the design, construction, and testing of practical analog and interface circuits, with emphasis on applications of operational amplifiers. No prior experience with electronics is required. Basic linear and nonlinear elements and circuits are studied, including amplifiers, filters, oscillators and other signal conditioning circuits. Each week includes a 45 minute lecture/recitation and a 2½ hour laboratory. 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 2 a or Ph 12 a, Ma 2, Ph 3, Ph 2 b or Ph 12 b (may be taken concurrently), Ma 3 (may be taken concurrently). A laboratory introduction to experimental physics and data analysis. Experiments use research-grade equipment and techniques to investigate topics in classical electrodynamics, resonance phenomena, waves, and other physical phenomena. Students develop critical, quantitative

evaluations of the relevant physical theories; they work individually and choose which experiments to conduct. Each week includes a 30-minute individual recitation and a 3 hour laboratory. Instructors: Rice, Politzer.

Ph 7. Physics Laboratory. *9 units; third term. Prerequisites: Ph6, Ph2b or Ph12b, Ph2c or Ph12c taken concurrently.* A laboratory course continuing the study of experimental physics introduced in Physics 6. The course introduces some of the equipment and techniques used in quantum, condensed matter, nuclear, and particle physics. The menu of experiments includes some classics which informed the development of the modern quantum theory, including electron diffraction, the Stern-Gerlach experiment, Compton scattering, and the Mössbauer Effect. The course format follows that of Physics 6: students work individually and choose which experiments to conduct, and each week includes a 30 minute individual recitation and a 3 hour laboratory. 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: Spiropulu.

FS/Ph 11 abc. Freshman Seminar: Beyond Physics. *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 wavefunction, one-dimensional bound states, scattering, and tunneling;

thermodynamics, introductory kinetic theory, and quantum statistics. Instructors: Chen, Filippone, Simmons-Duffin.

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); second, third terms. 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, Weinstein.

Ph 50 ab. Caltech Physics League. 3 units (1-0-2); first, second terms. Prerequisites: Ph 1 abc. This course serves as a physics club, meeting weekly to discuss and analyze real-world problems in 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. Instructors: Refael, Patterson.

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. Prerequisites: Ph 7 or instructor's permission. Advanced preparation for laboratory research. Dual emphasis on

practical skills used in modern research groups and historic experiments that illuminate important theoretical concepts. Topics include advanced signal acquisition, conditioning, and data processing, introductions to widely-used optical devices and techniques, laser-frequency stabilization, and classic experiments such as magnetic resonance, optical pumping, and doppler-free spectroscopy. Fundamentals of vacuum engineering, thin-film sample growth, and cryogenics are occasionally offered. Special topics and student-led projects are available on request. Instructors: Black, Libbrecht.

Ph 78 abc. Senior Thesis. 9 units; first, second, third terms. *Prerequisites:* To register for this course, the student must obtain approval of the chair of the Physics Undergraduate Committee (Ken Libbrecht). Open only to senior physics majors. This research must be supervised by a faculty member, the student's 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.

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 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. Offered in alternate years. Not offered 2019–20.

Ap/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:* Ph1abc, Ma2, or equivalent. A laboratory course intended for graduate students, it covers the design, construction, and testing of simple, practical analog and interface circuits useful for signal conditioning and experiment control in the laboratory. No prior experience with electronics is required. Students will use operational amplifiers, analog multipliers, diodes, bipolar transistors, and passive circuit elements. Each week includes a 45 minute lecture/recitation and a 2½ hour laboratory. The course culminates in a two-week project of the student's choosing.

Ph 106 abc. Topics in Classical Physics. 9 units (4-0-5); 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. Ph106a will be devoted to mechanics, including Lagrangian and Hamiltonian formulations of mechanics, small oscillations and normal modes, central forces, and rigid-body motion. Ph106b will be devoted to fundamentals of electrostatics, magnetostatics, and electrodynamics, including boundary-value problems, multipole expansions, electromagnetic waves, and radiation. It will also cover special relativity. Ph106c will cover advanced topics in electromagnetism and an introduction to classical optics. Instructors: Weinstein, Golwala, Hutzler.

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 abc. Physics of Measurement. 9 units (3-0-6); first, third terms. Prerequisites: Ph127, APh 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. Part c not offered in 2019–20. Instructor: Roukes.

CS/Ph 120. Quantum Cryptography. 9 units (3-0-6); first term. For course description, see Computer Science.

Ph 121 abc. Computational Physics Lab. 6 units (0-6-0); first, second, third terms. Many of the recent advances in physics are attributed to progress in computational power. In the advanced computational lab, students will hone their computational skills by working through projects inspired by junior level classes (such as classical mechanics and E, statistical mechanics, quantum mechanics and quantum many-body physics). This course will primarily be in Py-

thon and Mathematica. This course is offered pass/fail. Instructors: Simmons-Duffin, Motrunich.

Ph 125 abc. Quantum Mechanics. 9 units (4-0-5); first, second, third terms. Prerequisites: Ma 2 ab, Ph 12 abc or Ph 2 ab, or equivalents. A one-year course in quantum mechanics and its applications, for students who have completed Ph 12 or Ph 2. Wave mechanics in 3-D, scattering theory, Hilbert spaces, matrix mechanics, angular momentum, symmetries, spin-1/2 systems, approximation methods, identical particles, and selected topics in atomic, solid-state, nuclear, and particle physics. Instructor: Wise.

Ph 127 abc. Statistical Physics. 9 units (4-0-5); 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. Instructors: Motrunich, Brandao.

Ph 129 abc. Mathematical Methods of Physics. 9 units (4-0-5); 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 covers probability and statistics in physics. Second term focuses on group theoretic methods in physics. Third term includes analytic and numerical methods for solving differential equations, integral equations, and transforms, and other applications of real analysis. The three terms can be taken independently. Instructors: Porter, Chen, Oguri.

Ph 135. Introduction to Condensed Matter. 9 units (3-0-6); first term. Prerequisites: Ph 125 abc or equivalent or instructor's permission. This course is an 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. Instructor: Refael.

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 ther-

modynamics, 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. Offered in alternate years. Not offered 2019–20.

Ph/APh 137 abc. Atoms and Photons. *9 units (3-0-6); first, second terms. Prerequisites: Ph 125 abc or equivalent, or instructor's permission.* This course will provide an introduction to the interaction of atomic systems with photons. The main emphasis is on laying the foundation for understanding current research that utilizes cold atoms and molecules as well as quantized light fields. First term: resonance phenomena, atomic/molecular structure, and the semi-classical interaction of atoms/molecules with static and oscillating electromagnetic fields. Techniques such as laser cooling/trapping, coherent manipulation and control of atomic systems. Second term: quantization of light fields, quantized light matter interaction, open system dynamics, entanglement, master equations, quantum jump formalism. Applications to cavity QED, optical lattices, and Rydberg arrays. Third term [not offered 19-20]: Topics in contemporary research. Possible areas include introduction to ultracold atoms, atomic clocks, searches for fundamental symmetry violations, synthetic quantum matter, and solid state quantum optics platforms. The emphasis will be on reading primary and contemporary literature to understand ongoing experiments. Instructors: Hutzler, Endres.

APh/Ph 138 ab. Quantum Hardware and Techniques. *9 units (3-0-6).* For course description, see Applied Physics.

Ph 139. Introduction to High Energy Physics. *9 units (3-0-6); third term. Prerequisites: Ph 125 abc or equivalent, or instructor's permission.* This course provides an 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. Instructor: Patterson.

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 Physics. *Units in accordance with work accomplished.* Undergraduate students registering for 6 or more units

of Ph 172 must provide a brief written summary of their work, not to exceed 3 pages, to the option rep at the end of the term. Approval of the student's research supervisor and departmental adviser must be obtained before registering. Graded pass/fail.

Ph 177. Advanced Experimental Physics. *9 units (0-4-5); second, third terms. Prerequisites: Ph 7, Ph 106 a, Ph 125 a or equivalents.* A one-term laboratory course which will require students to design, assemble, calibrate, and use an apparatus to conduct a nontrivial experiment involving quantum optics or other current research area of physics. Students will work as part of a small team to reproduce the results of a published research paper. Each team will be guided by an instructor who will meet weekly with the students; the students are each expected to spend an average of 4 hours/week in the laboratory and the remainder for study and design. Enrollment is limited. Permission of the instructors required. Instructors: Rice, Hutzler.

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

Ph 198. Special Topics in Physics. *Units in accordance with work accomplished.* Topics will vary year to year and may include hands-on laboratory work, team projects and a survey of modern physics research. Instructor: Staff.

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 2019–20.

Ph 201. Candidacy Physics Fitness. *9 units (3-0-6); third term.* The course will review problem solving techniques and physics applications from the undergraduate physics college curriculum. In particular, we will touch on the main topics covered in the written candidacy exam: classical mechanics, electromagnetism, statistical mechanics and quantum physics, optics, basic mathematical methods of physics, and the physical origin of everyday phenomena. Instructor: Endres.

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, Kapustin.

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. Not offered 2019–20.

Ph/CS 219 abc. Quantum Computation. 9 units (3-0-6); first, second terms. Prerequisites: Ph 125 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. Part c not offered in 2019–20. Instructors: Preskill, Brandao.

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, Kitaev.

Ph 229 ab. Advanced Mathematical Methods of Physics. 9 units (3-0-6); first term. Prerequisites: Ph 205 abc or equivalent. A course on conformal field theory and the conformal bootstrap. Students should have some background in quantum field theory. Topics will include the renormalization group, phase transitions, universality, scale vs. conformal invariance, conformal symmetry, operator product expansion, state-operator correspondence, conformal blocks,

the bootstrap equations, bootstrap in $d=2$ dimensions, numerical bootstrap methods in $d>2$, analytical bootstrap methods, introduction to AdS/CFT. Possible additional topics (time permitting) include superconformal field theories, entanglement entropy, monotonicity theorems, and conformal perturbation theory. Instructor: Kapustin.

Ph 230 ab. Elementary Particle Theory. 9 units (3-0-6); first term. *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: Zurek. Only offered in fall quarter in the 2019-20 academic year

Ph 236 abc. General 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. Offered in alternate years. Part c not offered in 2019-20. Instructors: Chen, Teukolsky.

Ph 237. Gravitational Radiation. 9 units (3-0-6); third term. *Prerequisites:* Ph 106 bc, Ph 12 b or equivalents. Special topics in Gravitational-wave Detection. Physics of interferometers, limits of measurement, coherent quantum feedback, noise, data analysis. Instructor: Adhikari.

Ph 242 ab. Physics Seminar. 4 units (2-0-2); first, second terms. An introduction to independent research, including training in relevant professional skills and discussion of current Caltech research areas with Caltech faculty, postdocs, and students. One meeting per week plus student projects. Registration restricted to first-year graduate students in physics. Instructor: Patterson.

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 2019-20.

Ph 300. Thesis Research. *Units in accordance with work accomplished.* Ph 300 is elected in place of Ph 172 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 20. Political-Economic Development and Material Culture. *9 units (3-0-6); second term.* During the 19th-century the American economy, despite the Civil War, caught up to and surpassed all European economies. How did the likes of Singer, John Deere and Seth Thomas -- latecomers to the markets they served—come to dominate those markets both domestically and internationally? Why did the technology of interchangeable parts and mass production become known as 'the American system' when much of that technology was imported from Europe? What role did government play in facilitating or thwarting innovation and economic growth? This course will explore such questions as reflected in the ordinary things people collect under the label 'antiques'. What do we learn from the fact that we can document a half dozen American manufacturers of apple peelers but not a single comparable European company? Why is the hand sewn quilt a nearly unique American folk art form and what does the evolution of quilting patterns tell us about technology and economic prosperity? What do baking powder cans as a category of collectible tell us about the politics of federal versus state regulation? Students will be expected to each choose a topic that asks such questions and to explore possible answers, all with an eye to understanding the interplay of economics, politics, and demography. Instructor: Ordeshook.

BEM/Ec/PS 80. Frontiers in Social Sciences. *1 unit (1-0-0).* For course description, see Business, Economics, and Management.

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); first, second terms. 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); first 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. Not offered 2019–20.

PS 122. Political Representation. 9 units (3-0-6); third term. Prerequisites: PS 12. Why does the U.S. Constitution feature separation of powers and protect states' rights? Should the Senate have a filibuster? When can Congress agree on the best policy for the country (and what does "best" even mean)? This course uses a rigorous set of tools including game theory and social choice to help students understand the effectiveness of American democracy to represent diverse interests. Using the tools, we study U.S. electoral systems, Congress, federalism, and the courts, with a focus on understanding how the country has tried to overcome the challenges of group decision making and the inevitable conflicts that arise between the branches of government and divided political interests. Students will leave the course with a deeper understanding of how rules and strategy shape U.S. democracy. Not offered 2019–20.

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 125. Analyzing Political Conflict and Violence. 9 units (3-0-6);

second term. This course examines the causes of and solutions for conflict and violence: Why do wars occur and how do we stop them? We cover topics such as terrorism, ethnic violence, civil wars, the Israeli-Palestinian conflict, repression, revolutions, and inter-state wars. We study these phenomena using the rational choice framework and modern tools in data analysis. The goals of the class are to explain conflicts and their terminations as outcomes of strategic decision-making and to understand the empirical strengths and weakness of current explanations. Instructor: Gibilisco.

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 2019–20.

PS 132. Formal Theories in Political Science. 9 units (3-0-6);

first term. *Prerequisites:* PS 12 and Ec/PS 172. 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); first term.

The purpose of this course is to understand legislative elections. The course will study, for example, what role money plays in elections and why incumbents do better at the polls. It will also examine how electoral rules impact the behavior both of candidates and

voters, and will explore some of the consequences of legislative elections, such as divided government. Not offered 2019–20.

PS/SS 139. Comparative Politics. 9 units (3-0-6); third term.

Prerequisites: PS 12. This course offers a broad introduction to the theoretical and empirical research in comparative political economy. An emphasis will be placed on the parallel process of political and economic development and its consequences on current democratic political institutions such as: electoral rules, party systems, parliamentary versus presidential governments, legislatures, judicial systems, and bureaucratic agencies as exemplified in central bank politics. We will study the differential impact of these political institutions on the type of policies they implement and the economic outcomes they produce. The main objective of the course will be to assess the robustness of the analyzed theories in light of their empirical support, coming mainly from statistical analysis. Instructor: Lopez-Moctezuma.

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. Instructor: Kiewiet.

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

Ec/PS 160 abc. Laboratory Experiments in the Social Sciences.

9 units (3-3-3). For course description, see Economics.

PS/Ec 172. Game Theory. 9 units (3-0-6); third term. *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 13. Introduction to Cognitive Neuroscience. 9 units (3-0-6);

third term. This course will provide an introduction to what we know

about the fascinating link between the brain, the mind, and behavior. We will start with a basic review of the brain as a biological organ, its evolution, development, and its basic operations including visual and other senses. Next, we will discuss how the brain gives rise to a wide variety of complex behaviors, memory, social and emotional behaviors. The course will finally introduce students to the wider neurophilosophical questions concerning freewill, death and morality. Instructor: Mobbs.

Psy 25. Reading and Research in Psychology. *Units determined by the instructor.* Not available for credit toward humanities–social science requirement. Written report required. Graded pass/fail. Not offered 2019–20.

Psy 90. Applied Neuropsychology of Learning. *9 units (3-0-6); first term.* An introduction to the neuropsychological mechanisms associated with learning and creativity, and to how different factors and behaviors impede and enhance them. No previous coursework in psychology or neuroscience is required. The course includes labs in which the students will test various hypothesis about their own learning processes. Graded or P/F. Note that this course can be used to fulfill the overall HSS core requirements, but does not count towards the introductory or advanced social science requirement. Offered alternating years. Not offered 2019–20.

Psy 101. Selected Topics in Psychology. *Units determined by arrangement with the instructor; offered by announcement.* Instructor: Staff.

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

Psy/CNS 105 ab. Frontiers in Neuroeconomics. *5 units (1.5-0-3.5); second 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 inter-temporal 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. Instructor: O'Doherty.

Ec/Psy 109 ab. Frontiers in Behavioral Economics. 9 units (3-0-6). For course description, see Economics.

Psy 115. Social Psychology. 9 units (3-0-6); *first term*. The study of how people think about other people and behave toward or around others. Topics include social cognition and emotions (theory of mind and empathy), their development from childhood to old age, impairments in social functions, altruism and cooperation, social groups (ingroup and outgroup), attribution and stereotypes. The class also presents evidence on how these social phenomena are implemented in the human brain and introduces behavioral and neuroscientific methods used in social psychology and social neuroscience. Instructor: Dubois.

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 2019–20.

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 2019–20.

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

Psy/CNS 132. Computational Reinforcement-learning in Biological and Non-biological Systems. 9 units (3-0-6); *third term*. Reinforcement-learning concerns the computational principles by which animals and artificial agents can learn to select actions in their environment in order to maximize their future rewards. Over the past 50 years there has been a rich interplay between the development and application of reinforcement-learning models in artificial intelligence, and the investigation of reinforcement-learning in biological systems, including humans. This course will review this rich literature, covering the psychology of animal-learning, the neurobiology of reward and reinforcement, and the theoretical basis and application of reinforcement-learning models to biological and non-biological systems. Instructor: O'Doherty.

Psy 133. Computation, Cognition and Consciousness. 9 units (3-0-6); *second term*. This course will critically examine the impact of recent advances in computational neuroscience for central prob-

lems of philosophy of mind. Beginning with a historical overview of computationalism (the thesis that mental states are computational states), the course will examine how psychological explanation may be understood in computational terms across a variety of levels of description, from sub-neuronal and single neuron computation to circuit and network levels. Specific issues will include: whether computation provides unifying psychological principles across species; whether specific mental states such as pain are computational states; digital/analog computation, dynamical systems, and mental representation; whether conscious experience can be understood as a computational process. Not offered 2019–20.

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

PI/CNS/NB/Bi/Psy 161. Consciousness. 9 units (3-0-6). For course description, see Philosophy.

CNS/Bi/Psy/NB 176. Cognition. 9 units (4-0-5); third term. For course description, see Computation and Neural Systems.

Psy/Bi/CNS 255. Topics in Emotion and Social Cognition. 9 units (3-0-6); third term. *Prerequisites:* Bi/CNS/NB/Psy 150 or instructor's permission. Emotions are at the forefront of most human endeavors. Emotions aid us in decision-making (gut feelings), help us remember, torment us, yet have ultimately helped us to survive. Over the past few decades, we have begun to characterize the neural systems that extend from primitive affective response such as fight or flight to the complex emotions experienced by humans including guilt, envy, empathy and social pain. This course will begin with an in-depth examination of the neurobiological systems that underlie negative and positive emotions and move onto weekly discussions, based on assigned journal articles that highlight both rudimentary and complex emotions. The final weeks will be devoted to exploring how the neurobiological systems are disrupted in affective disorders including anxiety, aggression and psychopathy. In addition to these discussions and readings, each student will be required to write a review paper or produce a short movie on a topic related to one of the emotions discussed in these seminars and its underlying neural mechanisms. Instructor: Mobbs.

Psy 283 abc. Graduate Proseminar in Social and Decision Neuroscience. 3 units (1.5-0-1.5); first, second, and third terms. The course involves student presentations of their research, reading and discussion of recent research in social and decision neuroscience, and development of professional skill such as scientific writing and speaking, research ethics, writing grants and peer review. This course is only open to graduate students in the Social and Decision

Neuroscience, Computational and Neural Systems and Social Science PhD programs. Instructors: Camerer, Rangel, Camerer.

Psy/CNS 285. Topics in Social, Cognitive, and Decision Sciences. 3 units (3-0-0); second term. Select faculty will present their research background, methods, and a sampling of current questions/studies. Background readings and pdf of presentation will be provided. Not offered 2019–20.

SCIENTIFIC AND ENGINEERING COMMUNICATION

SEC 10. Technical Seminar Presentations. 3 units (3-0-0); first, second, third terms; (Seniors required to take this course are given priority in registration.). The purpose of this course is to equip students with the skills, knowledge, and experience necessary to give effective oral presentations. The course will include a mix of formal instruction, group discussions, practice presentations, and individual feedback. Limited enrollment. May not be repeated for credit. Instructor: Javier.

SEC 11. Written Academic Communication in Engineering and Applied Science. 3 units (1-0-2); terms to be arranged. This class provides the opportunity for students to gain experience in academic 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 an academic genre on that topic. Appropriate genres include the engineering report, review paper, or a peer-reviewed journal paper. Students will receive instruction in academic discourse in engineering and applied sciences as well as substantial feedback on their work-in-progress. This course is recommended for students who plan to attend graduate school or who wish to work toward a senior thesis or academic publication. Fulfills the Institute scientific writing requirement. Enrollment is limited to students in E&AS options and priority is given to seniors. Instructor: TBD.

SEC 12. Written Professional Communication in Engineering and Applied Sciences. 3 units (1-0-2); Terms to be arranged. *Prerequisites:* None. This class introduces students to common workplace genres of writing in professional (non-academic) fields in engineering and the applied sciences. Students will compose professional technical writing in multiple genres and consider the varied audiences and goals of writing in various engineering and applied sciences industries. Genres covered may include specifications; proposals; progress reports; recommendation reports; code

documentation; contracts, patents, and trademarks; user manuals or instructions; formal memos; business emails; or instant message communication. This course is recommended for students who plan to seek jobs in industry. Fulfills the Institute scientific writing requirement. Enrollment is limited to students in E&AS options and priority is given to seniors. Instructor: TBD.

SEC 13. Written Communication about Engineering and Applied Sciences to Non-Experts. *3 units (1-0-2); Terms to be arranged. Prerequisites: None.* Engineers and applied scientists often work on highly technical, specialized projects. However, their work often is of interest to readers with varied levels of area and technical expertise—including investors, community stakeholders, government regulators, consumers, voters, students, and enthusiasts. This course introduces students to diverse types of writing about technical engineering and applied science topics intended for these “non-expert” readers who lack some or all of the technical knowledge the author has. Students will compose multiple texts written for different purposes and to different types of non-expert readers. This course is recommended for students who may plan entrepreneurial, non-profit, or government careers, where communication to non-experts is crucial to success. It may also interest students who enjoy public advocacy or creative writing about technical topics. Fulfills the Institute scientific writing requirement. Enrollment is limited to students in E&AS options and priority is given to seniors. Instructor: TBD.

SEC 100. Special Topics in Scientific and Engineering Communication. *Units to be arranged; terms to be arranged in consultation with the instructor.* Content may vary from year to year, at a level suitable for advanced undergraduate or graduate students. Topics will be chosen to meet the emerging needs of students. Instructor: Javier.

E/SEC 102. Scientific and Technology Entrepreneurship. *9 units (3-0-6).* For course description, see Engineering.

E/SEC 103. Management of Technology. *9 units (3-0-6).* For course description, see Engineering.

SEC 111. Effective Communication Strategies for Engineers and Scientists. *6 units (3-0-3); third term. Prerequisites: none.* This graduate course offers instruction and practice in written and oral communication for scientists and engineers. The course is designed to increase students’ effectiveness in communicating complex technical information to diverse audiences and to deepen their understanding of communication tools and techniques. Students will explore scientific storytelling through multiple communication genres, including research manuscripts and presentations, visual

narratives, and traditional and social media channels. In-class workshops will provide students with the opportunity to revise their work and consider feedback from instructors and peers. (Registration by application only, and EAS graduate students are given priority.) Instructor: Javier.

SEC 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. Instructor: to be determined.

SEC 130. Science Activation: Bringing Science to Society. *6 units (3-0-3); second term. Prerequisites: none.* Working with policy makers is more than science communication. It requires a bilateral approach to exploring complex problems and solutions that encompass societal objectives as well as physical requirements. An intellectual understanding of the differences communication norms in the research and policy realms can help scientists make better decisions about how to communicate about their work and engage with policy makers to get it used. This course combines analysis of the differences in communication norms with practical experience in communicating and developing relationships with elected officials and their staffs. Instructor: Lucy Jones and John Bwarie.

SOCIAL SCIENCE

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.

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). For course description, see Economics.

Ec/SS 129. Economic History of the United States. 9 units (3-0-6). For course description, see Economics.

Ec/SS 130. Economic History of Europe from the Middle Ages to the Twentieth Century. 9 units (3-0-6). For course description, see Economics.

PS/SS 139. Comparative Politics. 9 units (3-0-6). For course description, see Political Science.

CS/SS/Ec 149. Algorithmic Economics. 9 units (3-0-6). For course description, see Computer Science.

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: Tamuz, Saito, Pomatto.

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, Lopez-Moctezuma.

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 neo-classical 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: Doval, Echenique, Palfrey.

SS 209. Behavioral Economics. 9 units (3-0-6); first 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. Instructor: Camerer.

SS 210 abc. Foundations of Political Economy. 9 units (3-0-6); first, second, third terms. Prerequisites: SS 202 c, SS 205 b. Mathematical theories of individual and social choice applied to problems of welfare economics and political decision making as well as to the construction of political economic processes consistent with stipulated ethical postulates, political platform formulation, the theory of political coalitions, and decision making in political organizations. Instructors: Gibilisco, Agranov.

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: Doval, Echenique/Pomatto, Saito.

SS 213 abc. Financial Economics. 9 units (3-2-4); First, second, third terms. Mathematical finance: Pricing financial derivatives, risk management, and optimal portfolio selection. Methods of stochastic, Ito calculus for models driven by Brownian motion. Asset pricing theory: Mean-variance theory, information economics, continuous-time finance and differential equations, intertemporal consumption-based asset pricing theories, recent developments in intermediary-based and behavioral asset pricing theories. Behavioral finance: Empirical facts about asset prices, investor trading behavior, and firm behavior. Psychology about investor preferences and beliefs. Behavioral finance models that explain empirical facts. Trading strategies implemented by hedge funds. Prescriptive behavioral finance that aims at helping individuals and institutions to make better financial decisions. Instructors: Jin.

SS 218. Neuroscience Applications to Economics and Politics. 9 units (3-0-6); second term. Topics in behavioral, affective, and social neuroscience that inform how individuals make economic

decisions. Applications of neuroscience ideas and methods to understanding choice under risk and uncertainty, temporal discounting and self-control, advertisement and preference formation, habit, addiction, and judgment bias. Not offered 2019–20.

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. Instructors: Shum, Xin, Sherman.

SS 223 abc. Topics in Theoretical and Applied Econometrics. 9 units (3-0-6); first, second, third terms. Prerequisites: SS 222 abc; may be repeated for credit. The courses in this sequence cover advanced methods and tools in econometrics, as well as their applications to a variety of topics in economics, including industrial organization, dynamic choice, information economics, political economy, market design, and behavioural economics. Instructors: Shum, Sherman, Xin.

SS 224. Social Science Data. 9 units (3-3-3); first term. This course provides broad coverage of empirical methods in the social sciences. This includes both methods of data collection and practical aspects of data analysis, as well as related issues of survey design, experimental design, techniques for handling large datasets, and issues specific to the collection and analysis of field and historical data. This course also provides students with hands-on experience with data. Open to Social Science graduate students only. Instructor: Alvarez.

SS 225. Experimentics. 9 units (3-0-6); third 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. Not offered 2019–20.

SS 228 abc. Applied Empirical Methods in the Social Sciences. 9 units (3-0-6); first, second, third terms. Course covers methods used in contemporary applied empirical work in a variety of social sciences. Topics covered include (a) maximum likelihood, Bayesian estimation, management and computation of large datasets, (b) reduced form methods like instrumental variables (IV), difference-in-differences (DID), natural experiments, event study and panel data methods, and (c) structural estimation. Emphasis is on the application of tools to substantive social science problems rather than sta-

tistical theory, in areas including political science, political economy, corporate finance, and accounting. Application focus will vary with instructor interests. Instructors: Katz, Ewens, Lopez-Moctezuma.

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: Hoffman, Rosenthal.

SS 231 abc. American and Comparative Politics. 9 units (3-0-6); first, second, third terms. Prerequisites: SS 202 abc, or permission of the instructor. An advanced graduate Social Science sequence in American and comparative politics. The sequence will focus on political institutions and behavior, introducing students to the important theories of American and comparative politics. Students will learn how historical, observational, and experimental data are used in American and comparative political analysis. Instructors: Alvarez, Staff.

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, organizations, committee processes, and election processes. Emphasis on experimental methods and techniques. Students will design and conduct experiments. May be repeated for credit with instructor's permission. Instructor: Plott.

SS 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 2019–20.

SS 282 abc. Graduate Proseminar in Social Science. 3 units (1.5-0-1.5); 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. Instructors: Gibilisco, Doval.

SS 299. Writing. 6 units (3-0-3); summer term. This course is designed for students to improve their ability for written expression in the English language. This course is only open to graduate students

in the Social Decision Neuroscience and Social Science Ph.D. programs. Instructor: Staff.

SS 300. Research in Social Science. *Units to be arranged.*

STUDENT ACTIVITIES

SA 15 abc. Student Publications. *SA 15a 5 units (2-0-3), first term; SA 15bc 4 units (1-0-3), second and third terms. Prerequisites: SA 15a is a prerequisite for SA 15b and SA 15c.* This course will enable students to produce quality, journalistically-crafted stories for the Tech newspaper. It will teach journalistic values of clarity, accuracy, fairness and balance, and acquaint the students with the primary elements of journalism, including reporting, basic story structure and news/opinion-writing distinctions. Students will produce feature stories for the Tech (with assigned art or graphics) about campus life and activities, profiles of campus faculty or staff, and issues of campus community interest. May be re-taken for credit. Instructor: Kipling.

SA 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.

SA 42. Computer Science Education in K-14 Settings Practicum. *4 units (0-2-2); first, second, third terms. Prerequisites: CS 42.* This course is a follow-on for students who have already taken CS 42 and would like to continue as part of a teaching group partnered with a local school or community college. Each week students are expected to spend about 2 hours teaching and 2 hours developing curricula. Students may take SA 42 multiple times. Graded pass/fail only. Not offered first term 2019–20. Instructor: Ralph.

SA 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 www.deans.caltech.edu/Services/student_taught_courses.

SA 80 abc. Health Advocates. *3 units (1-1-1); first, second, third terms.* A course designed to involve students with health care and education, develop familiarity with common college health prob-

lems, 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: Staf.

SA 81 ab. Peer Advocates. *3 units (1-1-1); first and third terms.* A course designed to involve students with appropriate peer support and education, develop familiarity with common college mental health problems, and provide peer mental health support to students on and off campus. Peer Advocates will begin the course in the spring term prior to the year of service, and continue coursework in the following fall term. Spring term: Active listening skills, identifying students in distress, suicide prevention training using the QPR (Question, Persuade, Refer) model; Fall term: Lectures and discussions on substance abuse, dating violence, sexual assault, depression, and other relevant mental health topics, as well as ongoing consultation about practical experience. Enrolled with permission only. Instructor: Staff.

VISUAL CULTURE

Hum/VC 49. Consuming Victorian Media. *9 units (3-0-6).* For course description, see Humanities.

Hum/VC 50. Introduction to Film. *9 units (3-0-6); third term.* For course description, see Humanities.

VC 60. Art/Media. *Units to be determined by the instructor; offered by announcement.* A practice-based course taught by a visiting artist in residence. See registrar's announcement for details. Instructor: TBD.

VC 70. Traditions of Japanese Art. *9 units (3-0-6); third 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 2019-20.

VC 72. Data, Algorithms and Society. *9 units (3-0-6); third term.* For course description, see CS/IDS 162. Taught concurrently

with CS/IDS 162 and can only be taken once as VC 72 or CS/IDS 162. Instructors: Mushkin, Ralph.

E/VC 88. Critical Making. 9 units (3-0-6). For course description, see Engineering.

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

VC 104. French Cinema. 9 units (3-0-6). For course description, see L 104. Not offered 2019–20. Instructor: Orcel.

En/VC 108. Volcanoes. 9 units (3-0-6). For class description, see English.

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

En/VC 117. Picturing the Universe. 9 units (3-0-6). For class description, see English.

L/VC 153. Refugees and Migrants' Visual and Textual Representations. 9 units (3-0-6). For course description, see Languages.

En/VC 160 ab. Classical Hollywood Cinema. 9 units (3-0-6). For course description, see English.

En/VC 161. The New Hollywood. 9 units (3-0-6). For course description, see English.

VC 169. The Arts of Dynastic China. 9 units (3-0-6); *third 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: Wolfram.

VC 170. Special Topics in Visual Culture. 9 units (3-0-6); *offered by announcement.* An advanced humanities course on a special topic in visual culture. Topics may include art history, film, digital and print media, architecture, photography or cartography. It is usually taught by new or visiting faculty. The course may be re-taken for credit except as noted in the course announcement. Limited to 15 students. See registrar's announcement for details. Instructor: Staff.

VC 171. 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. Not offered 2019–20.

H/HPS/VC 185. Angels and Monsters: Cosmology, Anthropology, and the Ends of the World. *9 units (3-0-6).* For course description, see History.

H/HPS/VC 186. From Plato to Pluto: Maps, Exploration and Culture from Antiquity to the Present. *9 units (3-0-6).* For course description, see History.

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, Sarmiento.

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 posi-

tion, 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. Instructor: Daley.

Wr 3. Reading and Composing Academic Writing. *9 units (1-0-8); 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. Instructor: Daley.

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. Instructor: Hall.

Wr 50. Tutorial in Writing. *1-3 units to be arranged; first, second, third terms.* 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. Instructor: Hall.

En/Wr 84. Writing About Science. *9 units (3-0-6); third term.* For course description, see English.

ESL/Wr 107. Graduate Writing Seminar. *6 units (3-0-3).* For course description, see English as a Second Language.

ESL/Wr 108. Intermedia Graduate Writing Seminar. 6 units (3-0-3). For course description, see English as a Second Language.