PE 89 ab. Intercollegiate Fencing Team (Men and Women). *3 units; first, second terms.* Coach: Corbit.

PE 90 abc. Intercollegiate Water Polo Team (Men and Women). *3 units; first term Men; second, third term Women.* Coach: Staff.

PE 91 ab. Intercollegiate Basketball Team (Men). *3 units; first, second terms.* Coach: Eslinger.

PE 92. Intercollegiate Soccer Team (Men). *3 units; first term.* Coach: Murray

PE 93 ab. Intercollegiate Baseball Team (Men). *3 units; second, third terms.* Coach: Mark.

PE 95 ab. Intercollegiate Tennis Team (Men). *3 units; second, third terms.* Coach: Gamble.

PE 96 ab. Intercollegiate Tennis Team (Women). *3 units; second, third terms.* Coach: Gamble.

PE 97. Intercollegiate Cross-Country Team (Men and Women). *3 units; first term.* Coach: Raphelson.

PE 99. Intercollegiate Volleyball Team (Women). *3 units; first term.* Coach: Gardner.

PHYSICS

Ph 1 abc. Classical Mechanics and Electromagnetism. *9 units (4-0-5); first, second, third terms.* The first year of a two-year course in introductory classical and modern physics. Topics: Newtonian mechanics in Ph 1 a; electricity and magnetism, and special relativity, in Ph 1 b, c. Emphasis on physical insight and problem solving. Ph 1 b, c is divided into two tracks: the Practical Track emphasizing practical electricity, and the Analytic Track, which teaches and uses methods of multivariable calculus. Students enrolled in the Practical Track are encouraged to take Ph 8 bc concurrently. Students will be given information helping them to choose a track at the end of fall term. Instructors: Hsieh, Martin, Alicea.

Ph 2 abc. Waves, Quantum Mechanics, and Statistical Physics. *9 units (3-0-6) ; first, second, third terms. Prerequisites: Ph 1 abc, Ma 1 abc.* An introduction to several areas of physics including applications in modern science and engineering. Topics include discrete and continuous oscillatory systems, wave mechanics, applications in telecommunications and other areas (first term); foundational quantum concepts, the quantum harmonic oscillator, the Hydrogen atom, applications in optical and semiconductor systems (second term); ensembles and statistical systems, thermodynamic laws, applications in energy technology and other areas (third term). Although best taken in sequence, the three terms can be taken independently. Instructor: Martin, Politzer, Cheung, Filippone.

Ph 3. Physics Laboratory. *6 units (0-3-3); first, second, third terms. Prerequisite: Ph 1 a or instructor's permission.* An introduction to experimental techniques and instruments used in the physical sciences, covering topics in classical mechanics, basic electronic circuits, and optics. Special emphasis is given to data analysis techniques based on modern statistical methods. The weekly structure of the course includes one three-hour laboratory session, a conference with the instructor, a set of pre-lab problems, and analysis of experimental results. Graded pass/fail unless a letter grade is requested. Only one term may be taken for credit. Instructors: Black, Libbrecht.

FS/Ph 4. Freshman Seminar: Astrophysics and Cosmology with Open Data. *6 units (3-0-3);.* For course description, see Freshman Seminar.

Ph 5. Analog Electonics for Physicists. *9 units (0-5-4); first term. Prerequisites: Ph 1 abc, Ph 3, or equivalents (Ph 8 may be subsituted for Ph 3).* A laboratory course focusing on practical electronic circuits, with emphasis on analog electronics. The following topics are studied: RC circuits, electrical oscillations, operational amplifiers, diodes and transistors, combining circuit elements, and computer data acquisition. The course culminates in a two-week project of the student's choosing. Instructors: Rice, Libbrecht.

Ph 6. Physics Laboratory. *9 units; second term. Prerequisites: Ph 1 abc, Ph 2 b or Ph 12 b (or taken concurrently), and Ph 3 or equivalent.* Experiments in electromagnetic phenomena such as electromagnetic induction, properties of magnetic materials, and high-frequency circuits. Mobility of ions in gases; precise measurement of the value of e/m of the electron. Instructors: Rice, Politzer.

Ph 7. Physics Laboratory. *9 units; third term. Prerequisites: Ph 6.* Experiments in atomic and nuclear physics, including studies of the Balmer series of hydrogen and deuterium, the decay of radioactive nuclei, absorption of X rays and gamma rays, ratios of abundances of isotopes, and the Stern-Gerlach experiment. Instructors: Rice, Politzer.

Ph 8 bc. Experiments in Electromagnetism. *3 units (0-3-0); second, third terms. Prerequisite: Ph 1 a.* A two-term sequence of experiments that parallel the material of Ph 1 bc. It includes measuring the force between wires with a homemade analytical balance, measuring properties of a 1,000-volt spark, and building and studying a radio-wave transmitter and receiver. The take-home experiments are constructed from a kit of tools and electronic parts. Measurements are compared to theoretical expectations. Instructor: Spiropulu.

FS/Ph 9. Freshman Seminar: The Science of Music. *6 units (2-0-4).* For course description, see Freshman Seminar.

Ph 10. Frontiers in Physics. *3 units (2-0-1); first term. Open for credit to freshmen and sophomores.* Weekly seminar by a member of the physics department or a visitor, to discuss his or her research at an introductory level; the other class meetings will be used to explore background material related to seminar topics and to answer questions that arise. The course will also help students find faculty sponsors for individual research projects. Graded pass/fail. Instructor: Prince.

FS/Ph 11 abc. Research Tutorial. *6 units (2-0-4).* For course description, see Freshman Seminar.

Ph 12 abc. Waves, Quantum Physics, and Statistical Mechanics. *9 units (4-0-5); first, second, third terms. Prerequisites: Ph 1 abc, Ma 1 abc, or equivalents.* A one-year course primarily for students intending further work in the physics option. Topics include classical waves; wave mechanics, interpretation of the quantum wave-function, one-dimensional bound states, scattering, and tunneling; thermodynamics, introductory kinetic theory, and quantum statistics. Instructors: Prince, Filippone, Zmuidzinas.

FS/Ph 15. Freshman Seminar: Dance of the Photons. *6 units (2-0-4).* For course description, see Freshman Seminar.

Ph 20. Computational Physics Laboratory I. *6 units (0-6-0); first, second, third terms. Prerequisites: CS 1 or equivalent.* Introduction to the tools of scientific computing. Use of numerical algorithms and symbolic manipulation packages for solution of physical problems. Python for scientific programming, Mathematica for symbolic manipulation, Unix tools for software development. Instructors: Prince, Mach.

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, Prince.

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, Prince.

Ph 50 abc. Caltech Physics League. *4 units (1-0-3); first, second terms. Prerequisite: Ph 1 abc.* This course serves as a physics club, meeting weekly to discuss and analyze real-world problems in the physical sciences. A broad range of topics will be considered, such as energy production, space and atmospheric phenomena, astrophysics, nano-science, and others. Students will use basic physics knowledge to produce simplified (and perhaps speculative) models of complex natural phenomena. In addition to regular assignments, students will also compete in solving challenge problems each quarter, with prizes given in recognition of the best solutions. Instructor: Refael.

Ph 70. Oral and Written Communication. *6 units (2-0-4); first, third terms.* Provides practice and guidance in oral and written communication of material related to contemporary physics research. Students will choose a topic of interest, make presentations of this material in a variety of formats, and, through a guided process, draft and revise a technical or review article on the topic. The course is intended for senior physics majors. *Fulfills the Institute scientific writing requirement.* Instructor: Hitlin.

Ph 77 abc. Advanced Physics Laboratory. *9 units (0-5-4); first, second, third terms. Prerequisite: Ph 7 or instructor's permission.* A three-term laboratory course to familiarize students with equipment and procedures used in the research laboratory. Experiments illustrate fundamental physical phenomena in atomic, optical, condensed-matter, nuclear, and particle physics, including NMR, laser-based atomic spectroscopy, gamma and X-ray spectroscopy, muon decay, weak localization, superconductivity, positron annihilation, and others. Instructors: Black, Libbrecht.

Ph 78 abc. Senior Thesis, Experimental. *9 units; first, second, third terms. Prerequisite: To register for this course, the student must obtain approval of the chair of the Physics Undergraduate Committee (Ed Stone). Open only to senior physics majors.* This research must be supervised by a faculty member, the student's thesis adviser. Laboratory work is required for this course. Two 15-minute presentations to the Physics Undergraduate Committee are required, one at the end of the first term and the second at the midterm week of the third term. The written thesis must be completed and distributed to the committee one week before the second presentation. Not offered on a pass/fail basis. See Note below.

Ph 79 abc. Senior Thesis, Theoretical. *9 units; first, second, third terms. Prerequisite: To register for this course, the student must obtain approval of the chair of the Physics Undergraduate Committee (Ed Stone). Open only to senior physics majors.* This research must be supervised by a faculty member, your thesis adviser. Two 15-minute presentations to the Physics Undergraduate Committee are required, one at the end of the first term and the second at the midterm week of the third term. The written thesis must be completed and distributed to the committee one week before the second presentation. Not offered on a pass/fail basis. See Note below.

Note: Students wishing assistance in finding an adviser and/or a topic for a senior thesis are invited to consult with the chair of the Physics Undergraduate Committee, or any other member of this committee. A grade will not be assigned in Ph 78 or Ph 79 until the end of the third term. P grades will be given the first two terms, and then changed at the end of the course to the appropriate letter grade.

Ph 101. Order-of-Magnitude Physics. *9 units (3-0-6); third term.* Emphasis will be on using basic physics to understand complicated systems. Examples will be selected from properties of materials, geophysics, weather, planetary science, astrophysics, cosmology, biomechanics, etc. Instructor: Phinney.

Ph 103. Atomic and Molecular Spectroscopy. *9 units (3-0-6); second term. Prerequisites: instructor's permission.* This course will review the basic spectroscopy of atoms and molecules, with applications to astrophysics, the terrestrial atmosphere, and the laboratory. Species to be discussed include hydrogen and simple multielectron atoms such as carbon, diatomic and polyatomic molecules, and some solids. Mechanisms and effects determining linewidths and lineshapes will be discussed for laboratory, atmospheric, and astrophysical conditions. Not offered 2016–17.

Ay/Ph 104. Relativistic Astrophysics. *9 units (3-0-6).* For course description, see Astrophysics.

Ph 105. Analog Electronics for Physicists. *9 units; first term. Prerequisites: Ph 1 abc, Ph 3, or equivalents (Ph 8 may be substituted for Ph 3).* A laboratory course focusing on practical electronic circuits, with emphasis on analog electronics. The following topics are studied: RC circuits, electrical oscillations, operational amplifiers, diodes and transistors, combining circuit elements, and computer data acquisition. The course culminates in a two-week project of the student's choosing. Instructors: Rice, Libbrecht.

Ph 106 abc. Topics in Classical Physics. *9 units (3-0-6); first, second, third terms. Prerequisites: Ph 2 ab or Ph 12 abc, Ma 2.* An intermediate course in the application of basic principles of classical physics to a wide variety of subjects. Roughly half of the year will be devoted to mechanics, and half to electromagnetism. Topics include Lagrangian and Hamiltonian formulations of mechanics, small oscillations and normal modes, boundary-value problems, multipole expansions, and various applications of electromagnetic theory. Instructors: Weinstein, Golwala.

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 and second 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. Instructor: Roukes.

CS/Ph 120. Quantum Cryptography. *9 units (3-0-6); first term.* For course description, see Computer Science.

Ph 125 abc. Quantum Mechanics. *9 units (3-0-6); first, second, third terms. Prerequisites: Ma 2 ab, Ph 12 abc or Ph 2 ab, or equivalents.* A one-year course in quantum mechanics and its applications, for students who have completed Ph 12 or Ph 2. Wave mechanics in 3-D, scattering theory, Hilbert spaces, matrix mechanics, angular momentum, symmetries, spin-$^1/_2$ systems, approximation methods, identical particles, and selected topics in atomic, solid-state, nuclear, and particle physics. Instructors: Brandao, Cheung.

Ph 127 abc. Statistical Physics. *9 units (3-0-6); first, second, third terms. Prerequisites: Ph 12 c or equivalent, and a basic understanding of quantum and classical mechanics.* A course in the fundamental ideas and applications of classical and quantum statistical mechanics. Topics to be covered include the statistical basis of thermodynamics; ideal classical and quantum gases (Bose and Fermi); lattice vibrations and phonons; weak interaction expansions; phase transitions; and fluctuations and dynamics. Instructor: Refael, Motrunich.

Ph 129 abc. Mathematical Methods of Physics. *9 units (3-0-6); first, second, third terms. Prerequisites: Ph 106 abc and ACM 95/100 ab or Ma 108 abc, or equivalents.* Mathematical methods and their application in physics. First term includes analytic and numerical methods for solving differential equations, integral equations, and transforms, and other applications of real analysis. Second term covers probability and statistics in physics. Third term focuses on group theoretic methods in physics. The three terms can be taken independently. Instructors: Porter, Chen.

Ph 135 abc. Applications of Quantum Mechanics. *9 units (3-0-6); first, second, third terms. Prerequisites: Ph 125 abc or equivalent.* Applications of quantum mechanics to topics in contemporary physics. First term: introduction to condensed matter which covers electronic properties of solids, including band structures, transport, and optical properties. Ph 135a is continued by Ph 223 ab in second and third terms. Second term: introduction to particle physics which includes Standard Model, Feynman diagrams, matrix elements, electroweak theory, QCD, gauge theories, the Higgs mechanism, neutrino mixing, astro-particle physics/cosmology, accelerators, experimental techniques, important historical and recent results, physics beyond the Standard Model, and major open questions in the field. Third term: an overview of modern Quantum Optics with particular emphasis on quantum measurement science, the quantum-classical interface, quantum networks, and quantum many-body physics with atoms and photons. The course will concentrate on the essential roles of manifestly quantum (i.e., nonclassical) and entangled states of light and matter. The course covers theoretical tools for analyses of coherent light-matter interactions including the quantum master equation, and will combine examples on both theory and experiment from the current research literature. This is a one-term class aimed at advanced undergraduates as well as beginning graduate students. Terms may be taken independently. Instructors: Yeh, Endres, Patterson.

Ph 136 abc. Applications of Classical Physics. *9 units (3-0-6); first, second, third terms. Prerequisites: Ph 106 abc or equivalent.* Applications of classical physics to topics of interest in contemporary "macroscopic" physics. Continuum physics and classical field theory; elasticity and hydrodynamics; plasma physics; magnetohydrodynamics; thermodynamics and statistical mechanics; gravitation theory, including general relativity and cosmology; modern optics. Content will vary from year to year, depending on the instructor. An attempt will be made to organize the material so that the terms may be taken independently. Ph 136a will focus on thermodynamics, statistical mechanics, random processes, and optics. Ph136b will focus on fluid dynamics, MHD, turbulence, and plasma physics. Ph 136c will cover an introduction to general relativity. Instructors: Hopkins, Phinney, Vallisneri.

Ph 171. Reading and Independent Study. *Units in accordance with work accomplished.* Occasionally, advanced work involving reading, special problems, or independent study is carried out under the supervision of an instructor. Approval of the instructor and of the student's departmental adviser must be obtained before registering. The instructor will complete a student evaluation at the end of the term. Graded pass/fail.

Ph 172. Research in Experimental Physics. *Units in accordance with work accomplished.* Students registering for 6 or more units of Ph 172 must give a 15-minute oral presentation to the Physics Undergraduate Committee at the Physics Undergraduate Research Seminar Day. Approval of the student's research supervisor and departmental adviser must be obtained before registering. Graded pass/fail.

Ph 173. Research in Theoretical Physics. *Units in accordance with work accomplished.* Students registered for 6 or more units of Ph 173 must give a 15-minute oral presentation to the Physics Undergraduate Committee at the Physics Undergraduate Research Seminar Day. Approval of the student's research supervisor and departmental adviser must be obtained before registering. Graded pass/fail.

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

Ph 199. Frontiers of Fundamental Physics. *9 units (3-0-6); third term. Prerequisites: Ph 125 abc, Ph 106 abc, or equivalent.* This course will explore the frontiers of research in particle physics and cosmology, focusing on the physics at the Large Hadron Collider. Topics include the Standard Model of particle physics in light of the discovery of the Higgs boson, work towards the characterization and measurements of the new particle's quantum properties, its implications on physics beyond the standard model, and its connection with the standard model of cosmology focusing on the dark matter challenge. The course is geared toward seniors and first-year graduate students who are not in particle physics, although students in particle physics are welcome to attend. Not offered 2016–2017.

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. Instructors: Refael, 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. Instructor: Wise.

Ph 217. Introduction to the Standard Model. *9 units (3-0-6); first term. Prerequisites: Ph 205 abc and Ph 236 abc, or equivalent.* An introduction to elementary particle physics and cosmology. Students should have at least some background in quantum field theory and general relativity. The standard model of weak and strong interactions is developed, along with predictions for Higgs physics and flavor physics. Some conjectures for physics beyond the standard model are introduced: for example, low-energy supersymmetry and warped extra dimensions. Not offered 2016-17.

Ph/CS 219 abc. Quantum Computation. *9 units (3-0-6); first, second, third terms. Prerequisite: Ph 129 abc or equivalent.* The theory of quantum information and quantum computation. Overview of classical information theory, compression of quantum information, transmission of quantum information through noisy channels, quantum error-correcting codes, quantum cryptography and teleportation. Overview of classical complexity theory, quantum complexity, efficient quantum algorithms, fault-tolerant quantum computation, physical implementations of quantum computation. Instructors: Kitaev, Preskill.

Ph/APh 223 ab. Advanced Condensed-Matter Physics. *9 units (3-0-6); second, third terms. Prerequisites: Ph 125 or equivalent, or instructor's permission.* Advanced topics in condensed-matter physics, with emphasis on the effects of interactions, symmetry, and topology in many-body systems. Ph/Aph 223a covers second quantization, Hartree-Fock theory of the electron gas, Mott insulators and quantum magnetism, bosonization, quantum Hall effects, and symmetry protected topological phases such as topological insulators. Ph/APh 223b will continue with BCS theory of superconductivity, Ginzburg-Landau theory, elements of unconventional and topological superconductors, theory of superfluidity, Bose-Hubbard model and bosonic Mott insulators, and some aspects of quantum systems with randomness. Instructors: Alicea, Chen.

Ph 229 abc. Advanced Mathematical Methods of Physics. *9 units (3-0-6); first, second terms only. Prerequisite: Ph 129 abc or equivalent.* Advanced topics in geometry and topology that are widely used in modern theoretical physics. Emphasis will be on understanding and applications more than on rigor and proofs. First term will cover basic concepts in topology and manifold theory. Second term will include Riemannian geometry, fiber bundles, characteristic classes, and index theorems. Third term will include anomalies in gauge-field theories and the theory of Riemann surfaces, with emphasis on applications to string theory. Instructor: Ooguri.

Ph 230 abc. Elementary Particle Theory. *9 units (3-0-6); second, third terms. Prerequisite: Ph 205 abc or equivalent.* Advanced methods in quantum field theory. First term: introduction to supersymmetry, including the minimal supersymmetric extension of the standard model, supersymmetric grand unified theories, extended supersymmetry, supergravity, and supersymmetric theories in higher dimensions. Second and third terms: nonperturbative phenomena in non-Abelian gauge field theories, including quark confinement, chiral symmetry breaking, anomalies, instantons, the 1/N expansion, lattice gauge theories, and topological solitons. Not offered 2016-17.

Ph 236 abc. Relativity. *9 units (3-0-6); first, second terms. Prerequisite: a mastery of special relativity at the level of Goldstein's* Classical Mechanics*, or of Jackson's* Classical Electrodynamics*.* A systematic exposition of Einstein's general theory of relativity and its applications to gravitational waves, black holes, relativistic stars, causal structure of space-time, cosmology and brane worlds. Not offered 2016–2017.

Ph 237. Gravitational Waves. *9 units (3-0-6); third term. Prerequisite: Ph 236 a.* The theory and astrophysical phenomenology of gravitational-wave sources (black holes, neutron stars, compact binaries, early-universe phenomena, etc.). Gravitational-wave detectors (LIGO, LISA, and others), and data analysis. Not offered 2016–17.

Ph 242 ab. Physics Seminar. *3 units (2-0-1); first, second terms.* Topics in physics emphasizing current research at Caltech. One two-hour meeting per week. Speakers will be chosen from both faculty and students. Registration restricted to first-year graduate students in physics; exceptions only with permission of instructor. Graded pass/fail. Instructor: Stone, Refael.

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. Instructors: Gukov, Kapustin.

Ph 300. Thesis Research. *Units in accordance with work accomplished.* Ph 300 is elected in place of Ph 172 or Ph 173 when the student has progressed to the point where research leads directly toward the thesis for the degree of Doctor of Philosophy. Approval of the student's research supervisor and department adviser or registration representative must be obtained before registering. Graded pass/fail.