

# PHYSICS (PHYSICS)

## **PHYSICS 100. Introduction to Observational Astrophysics. 4 Units.**

Designed for undergraduate physics majors but open to all students with a calculus-based physics background and some laboratory and coding experience. Students make and analyze observations using the telescopes at the Stanford Student Observatory. Topics covered include navigating the night sky, the physics of stars and galaxies, telescope instrumentation and operation, imaging and spectroscopic techniques, quantitative error analysis, and effective scientific communication. The course concludes with an independent project where student teams propose and execute an observational astronomy project of their choosing, using techniques learned in class to gather and analyze their data, and presenting their findings in the forms of professional-style oral presentations and research papers. Enrollment by permission. To get a permission number please complete form: <http://web.stanford.edu/~elva/physics100prelim.fb> If you have not heard from us by the beginning of class, please come to the first class session.

## **PHYSICS 104. Electronics and Introduction to Experimental Methods. 4 Units.**

Introductory laboratory electronics, intended for Physics and Engineering Physics majors but open to all students with science or engineering interests in analog circuits, instrumentation and signal processing. The first part of the course is focused on hands-on exercises that build skills needed for measurements, including input/output impedance concepts, filters, amplifiers, sensors, and fundamentals of noise in physical systems. Lab exercises include DC circuits, RC and diode circuits, applications of operational amplifiers, optoelectronics, synchronous detection, and noise in measurements. The second portion of the class is an instrumentation design project, where essential instrumentation for a practical lab measurement is designed, constructed and applied for an experiment. Example measurements can include temperature measurement in a cryostat, resistivity measurement of a superconducting material, measurement of the 2-D position of an optical beam, development of a high impedance ion probe and clamp for neuroscience, or other projects of personal interest. The course focuses on practical techniques and insight from the lab exercises, with a goal to prepare undergraduates for laboratory research. No formal electronics experience is required beyond exposure to concepts from introductory Physics or Engineering courses (Ohm's law, charge conservation, physics of capacitors and inductors, etc.). Recommended prerequisite: Physics 43 and 44 or Physics 63 and 64, or Engineering 40A or 40M.

## **PHYSICS 105. Intermediate Physics Laboratory I: Analog Electronics. 4 Units.**

Introductory laboratory electronics, designed for Physics and Engineering Physics majors but open to all students with science or engineering interests in analog circuits, instrumentation and signal processing. The course is focused on laboratory exercises that build skills needed for measurements, including sensors, amplification and filtering, and fundamentals of noise in physical systems. The hands-on lab exercises include DC circuits, RC and diode circuits, applications of operational amplifiers, non-linear circuits and optoelectronics. The class exercises build towards a lock-in amplifier contest where each lab section designs and builds a synchronous detection system to measure a weak optical signal, with opportunities to understand the limits of the design, build improvements and compare results with the other lab sections. The course focuses on practical techniques and insight from the lab exercises, with a goal to prepare undergraduates for laboratory research. No formal electronics experience is required beyond exposure to concepts from introductory Physics or Engineering courses (Ohm's law, charge conservation, physics of capacitors and inductors, etc.). Recommended prerequisite: Physics 43 or 63, or Engineering 40A or 40M.

## **PHYSICS 106. Experimental Methods in Quantum Physics. 4 Units.**

Experimental physics lab course aimed at providing an understanding of and appreciation for experimental methods in physics, including the capabilities and limitations, both fundamental and technical. Students perform experiments that use optics, lasers, and electronics to measure fundamental constants of nature, perform measurements at the atomic level, and analyze results. Goals include developing an understanding of measurement precision and accuracy through concepts of spectral-analysis of coherent signals combined with noise. We explore the fundamental limits to measurement set by thermal noise at finite temperature, as well as optical shot-noise in photo-detection that sets the standard quantum limit in detecting light. Spectroscopy of light emitted from atoms reveals the quantum nature of atomic energy levels, and when combined with theoretical models provides information on atomic structure and fundamental constants of nature (e.g. the fine structure constant that characterizes the strength of all electro-magnetic interactions, and the ratio of the electron mass to the proton mass,  $m_e/m_p$ ). Experiments may include laser spectroscopy to determine the interatomic potential, effective spring constant, and binding energy of a diatomic molecule, or measure the speed of light. This course will provide hands-on experience with semiconductor diode lasers, basic optics, propagation and detection of optical beams, and related electronics and laboratory instrumentation. For lab notebooks the class uses an integrated online environment for data analysis, curve fitting, (system is based on Jupyter notebooks, Python, and document preparation). Prerequisites: PHYSICS 40 series and PHYSICS 70, or 60 series, PHYSICS 120, PHYSICS 130; some familiarity with basic electronics is helpful but not required. Very basic programming in Python is needed, but background with Matlab, Origin, or similar software should be sufficient to come up to speed for the data analysis.

## **PHYSICS 107. Intermediate Physics Laboratory II: Experimental Techniques and Data Analysis. 4 Units.**

Experiments on lasers, Gaussian optics, and atom-light interaction, with emphasis on data and error analysis techniques. Students describe a subset of experiments in scientific paper format. Prerequisites: completion of PHYSICS 40 or PHYSICS 60 series, and PHYSICS 70 and PHYSICS 105. Recommended pre- or corequisites: PHYSICS 120 and 130. WIM.

## **PHYSICS 108. Advanced Physics Laboratory: Project. 5 Units.**

Have you ever wanted to dream up a research question, then design, execute, and analyze an experiment to address it, together with a small group of your fellow students? This is an accelerated, guided experimental research experience, resembling real frontier research. Phenomena that have been studied include magnetization of ferromagnets, quantum hall effect in graphene, interference in superconducting circuits, loss in nanomechanical resonators, and superfluidity in helium. But most projects pursued (drawn from condensed matter and recently also particle physics) have never been done in the class before. Our equipment and apparatus for Physics 108 are very flexible, not standardized like in most other lab classes. We provide substantial resources to help your team. Often, with instructors' help, students obtain unique samples from Stanford research groups. Prerequisite: PHYSICS 105, or other experience in electronics. Suggested but less critical: Physics 130 (many phenomena you might study build on quantum mechanics) and Physics 107 (experience with data analysis and useful measurement tools: lock-in amplifier, spectrum analyzer.) We recommend taking this class in junior year if possible, as it can inform post-graduation decisions and can empower the professor to write a powerful letter of recommendation.

**PHYSICS 110. Advanced Mechanics. 3-4 Units.**

Lagrangian and Hamiltonian mechanics. Principle of least action, Euler-Lagrange equations. Small oscillations and beyond. Symmetries, canonical transformations, Hamilton-Jacobi theory, action-angle variables. Introduction to classical field theory. Selected other topics, including nonlinear dynamical systems, attractors, chaotic motion. Undergraduates register for Physics 110 (4 units). Graduates register for Physics 210 (3 units). Prerequisites: MATH 131P or PHYSICS 111. Recommended prerequisite: PHYSICS 130. Same as: PHYSICS 210

**PHYSICS 111. Partial Differential Equations of Mathematical Physics. 4 Units.**

This course is intended to introduce students to the basic techniques for solving partial differential equations that commonly occur in classical mechanics, electromagnetism, and quantum mechanics. Tools that will be developed include separation of variables, Fourier series and transforms, and Sturm-Liouville theory. Examples (including the heat equation, Laplace equation, and wave equation) will be drawn from different areas of physics. Through examples, students will gain a familiarity with some of the famous special functions arising in mathematical physics. Prerequisite: MATH 53 or 63. Completing PHYSICS 40 or 60 sequences helpful.

**PHYSICS 112. Mathematical Methods for Physics. 4 Units.**

The course will focus on nonlinear dynamics and chaos and its applications in physics and other areas of science. Topics will include first-order differential equations and bifurcations, phase plane analysis, limit cycles, chaos, iterated maps, period doubling, fractals, and strange attractors. Applications will be drawn from traditional areas of physics as well as fields like systems biology, evolutionary game theory, and sociophysics. This course can be repeated for credit. Prerequisites: MATH 53 or equivalent.

**PHYSICS 113. Computational Physics. 4 Units.**

Numerical methods for solving problems in mechanics, astrophysics, electromagnetism, quantum mechanics, and statistical mechanics. Methods include numerical integration; solutions of ordinary and partial differential equations; solutions of the diffusion equation, Laplace's equation and Poisson's equation with various methods; statistical methods including Monte Carlo techniques; matrix methods and eigenvalue problems. Short introduction to Python, which is used for class examples and active learning notebooks; independent class projects make up more than half of the grade and may be programmed in any language such as C, Python or Matlab. No Prerequisites but some previous programming experience is advisable.

**PHYSICS 120. Intermediate Electricity and Magnetism I. 4 Units.**

Vector analysis. Electrostatic fields, including boundary-value problems and multipole expansion. Dielectrics, static and variable magnetic fields, magnetic materials. Maxwell's equations. Prerequisites: PHYSICS 43 or PHYS 63; MATH 52 and MATH 53. Pre- or corequisite: PHYS 111, MATH 131P or MATH 173. Recommended corequisite: PHYS 112.

**PHYSICS 121. Intermediate Electricity and Magnetism II. 4 Units.**

Conservation laws and electromagnetic waves, Poynting's theorem, tensor formulation, potentials and fields. Plane wave problems (free space, conductors and dielectric materials, boundaries). Dipole and quadrupole radiation. Special relativity and transformation between electric and magnetic fields. Prerequisites: PHYS 120 and PHYS 111 or MATH 131P or MATH 173; Recommended: PHYS 112.

**PHYSICS 130. Quantum Mechanics I. 4 Units.**

The origins of quantum mechanics and wave mechanics. Schrödinger equation and solutions for one-dimensional systems. Commutation relations. Generalized uncertainty principle. Time-energy uncertainty principle. Separation of variables and solutions for three-dimensional systems; application to hydrogen atom. Spherically symmetric potentials and angular momentum eigenstates. Spin angular momentum. Addition of angular momentum. Prerequisites: PHYSICS 65 or PHYSICS 70 and PHYSICS 111 or MATH 131P or MATH 173. MATH 173 can be taken concurrently. Pre- or corequisites: PHYSICS 120.

**PHYSICS 131. Quantum Mechanics II. 4 Units.**

Identical particles; Fermi and Bose statistics. Time-independent perturbation theory. Fine structure, the Zeeman effect and hyperfine splitting in the hydrogen atom. Time-dependent perturbation theory. Variational principle and WKB approximation. Prerequisite: PHYSICS 120, PHYSICS 130, PHYSICS 111 or MATH 131P, or MATH 173. Pre- or corequisite: PHYSICS 121.

**PHYSICS 134. Advanced Topics in Quantum Mechanics. 3-4 Units.**

Scattering theory, partial wave expansion, Born approximation. Additional topics may include nature of quantum measurement, EPR paradox, Bell's inequality, and topics in quantum information science; path integrals and applications; Berry's phase; structure of multi-electron atoms (Hartree-Fock); relativistic quantum mechanics (Dirac equation). Undergraduates register for PHYSICS 134 (4 units). Graduate students register for PHYSICS 234 (3 units). Prerequisite: PHYSICS 131. Same as: PHYSICS 234

**PHYSICS 14N. Quantum Information: Visions and Emerging Technologies. 3 Units.**

What sets quantum information apart from its classical counterpart is that it can be encoded non-locally, woven into correlations among multiple qubits in a phenomenon known as entanglement. We will discuss paradigms for harnessing entanglement to solve hitherto intractable computational problems or to push the precision of sensors to their fundamental quantum mechanical limits. We will also examine challenges that physicists and engineers are tackling in the laboratory today to enable the quantum technologies of the future.

**PHYSICS 15. Stars and Planets in a Habitable Universe. 3 Units.**

Is the Earth unique in our galaxy? Students learn how stars and our galaxy have evolved and how this produces planets and the conditions suitable for life. Discussion of the motion of the night sky and how telescopes collect and analyze light. The life-cycle of stars from birth to death, and the end products of that life cycle -- from dense stellar corpses to supernova explosions. Course covers recent discoveries of extrasolar planets -- those orbiting stars beyond our sun -- and the ultimate quest for other Earths. Intended to be accessible to non-science majors, material is explored quantitatively with problem sets using basic algebra and numerical estimates. Sky observing exercise and observatory field trips supplement the classroom work.

**PHYSICS 152. Introduction to Particle Physics I. 3 Units.**

Elementary particles and the fundamental forces. Quarks and leptons. The mediators of the electromagnetic, weak and strong interactions. Interaction of particles with matter; particle acceleration, and detection techniques. Symmetries and conservation laws. Bound states. Decay rates. Cross sections. Feynman diagrams. Introduction to Feynman integrals. The Dirac equation. Feynman rules for quantum electrodynamics and for chromodynamics. Undergraduates register for PHYSICS 152. Graduate students register for PHYSICS 252. (Graduate students will be required to complete additional assignments in a format determined by the instructor.) Prerequisite: PHYSICS 130. Pre- or corequisite: PHYSICS 131. Same as: PHYSICS 252

**PHYSICS 153. Introduction to String Theory, Quantum Gravity, and Black Holes. 3 Units.**

This course will begin with a basic introduction to the physics and mathematics of string theory and its relation to gravity. Following that we will study the quantum mechanics of black holes, and how string theory has impacted our understanding of these extreme gravitational objects. Prerequisites: 130 and 131.

**PHYSICS 155. Accelerators and Beams: Tools of Discovery and Innovation. 3 Units.**

Particle accelerators range in scale from sub-mm structures created using lithography on a silicon chip to the 27-km Large Hadron Collider in Switzerland based on superconducting magnets. Some accelerators generate beams that are only nanometers in size while others are used to make the brightest x-ray beams in the world. Accelerators are used for medicine, security, and industry as well as discovery science. A recent study shows that nearly 30% of the Nobel Prizes in Physics had a direct contribution from accelerators. This course will cover the fundamentals of particle beam acceleration and control. Topics will include radio-frequency acceleration, alternate gradient focusing, and collective effects where electromagnetic fields from the particle beam act back on the beam or on adjacent beams. Some experimental studies of beam physics may be performed at the SLAC National Accelerator Laboratory. Prerequisites: Special relativity at the level of Physics 61 or 70, or equivalent. Physics 120 and 121, or EE 142 and 242; Physics 121/EE 142 can be taken concurrently with class.

**PHYSICS 16. The Origin and Development of the Cosmos. 3 Units.**

How did the present Universe come to be? The last few decades have seen remarkable progress in understanding this age-old question. Course will cover the history of the Universe from its earliest moments to the present day, and the physical laws that govern its evolution. The early Universe including inflation and the creation of matter and the elements. Recent discoveries in our understanding of the makeup of the cosmos, including dark matter and dark energy. Evolution of galaxies, clusters, and quasars, and the Universe as a whole. Implications of dark matter and dark energy for the future evolution of the cosmos. Intended to be accessible to non-science majors, material is explored quantitatively with problem sets using basic algebra and numerical estimates.

**PHYSICS 160. Introduction to Stellar and Galactic Astrophysics. 3 Units.**

Radiative processes. Observed characteristics of stars and the Milky Way galaxy. Physical processes in stars and matter under extreme conditions. Structure and evolution of stars from birth to death. White dwarfs, planetary nebulae, supernovae, neutron stars, pulsars, binary stars, x-ray stars, and black holes. Galactic structure, interstellar medium, molecular clouds, HI and HII regions, star formation, and element abundances. Undergraduates register for PHYSICS 160. Graduate students register for PHYSICS 260. Pre-requisite: Physics 120 or permission of instructor. Recommended: Some familiarity with plotting and basic numerical calculations. Same as: PHYSICS 260

**PHYSICS 161. Introduction to Cosmology and Extragalactic Astrophysics. 3 Units.**

What do we know about the physical origins, content, and evolution of the Universe – and how do we know it? Students learn how cosmological distances and times, and the geometry and expansion of space, are described and measured. Composition of the Universe. Origin of matter and the elements. Observational evidence for dark matter and dark energy. Thermal history of the Universe, from inflation to the present. Emergence of large-scale structure from quantum perturbations in the early Universe. Astrophysical tools used to learn about the Universe. Big open questions in cosmology. Undergraduates register for Physics 161. Graduates register for Physics 261. (Graduate students will be required to complete additional assignments in a format determined by the instructor.) Prerequisite: PHYSICS 121 or equivalent. Same as: PHYSICS 261

**PHYSICS 166. Statistical Methods in Experimental Physics. 3 Units.**

Statistical methods constitute a fundamental tool for the analysis and interpretation of experimental physics data. In this course, students will learn the foundations of statistical data analysis methods and how to apply them to the analysis of experimental data. Problem sets will include data-sets from real experiments and require the use of programming tools to extract physics results. Topics include probability and statistics, experimental uncertainties, parameter estimation, confidence limits, and hypothesis testing. Students will be required to complete a final project. Same as: PHYSICS 266

**PHYSICS 17. Black Holes and Extreme Astrophysics. 3 Units.**

Black holes represent an extreme frontier of astrophysics. Course will explore the most fundamental and universal force – gravity – and how it controls the fate of astrophysical objects, leading in some cases to black holes. How we discover and determine the properties of black holes and their environment. How black holes and their event horizons are used to guide thinking about mysterious phenomena such as Hawking radiation, wormholes, and quantum entanglement. How black holes generate gravitational waves and powerful jets of particles and radiation. Other extreme objects such as pulsars. Relevant physics, including relativity, is introduced and treated at the algebraic level. No prior physics or calculus is required, although some deep thinking about space, time, and matter is important in working through assigned problems.

**PHYSICS 170. Thermodynamics, Kinetic Theory, and Statistical Mechanics I. 4 Units.**

Basic probability and statistics for random processes such as random walks. The derivation of laws of thermodynamics from basic postulates; the determination of the relationship between atomic substructure and macroscopic behavior of matter. Temperature; equations of state, heat, internal energy, equipartition; entropy, Gibbs paradox; equilibrium and reversibility; heat engines; applications to various properties of matter; absolute zero and low-temperature phenomena. Distribution functions, fluctuations, the partition function for classical and quantum systems, irreversible processes. Pre- or corequisite: PHYSICS 130.

**PHYSICS 171. Thermodynamics, Kinetic Theory, and Statistical Mechanics II. 4 Units.**

Mean-field theory of phase transitions; critical exponents. Ferromagnetism, the Ising model. The renormalization group. Dynamics near equilibrium: Brownian motion, diffusion, Boltzmann equations. Other topics at discretion of instructor. Prerequisite: PHYSICS 170. Recommended pre- or corequisite: PHYSICS 130.

**PHYSICS 172. Solid State Physics. 3 Units.**

Introduction to the properties of solids. Crystal structures and bonding in materials. Momentum-space analysis and diffraction probes. Lattice dynamics, phonon theory and measurements, thermal properties. Electronic structure theory, classical and quantum; free, nearly-free, and tight-binding limits. Electron dynamics and basic transport properties; quantum oscillations. Properties and applications of semiconductors. Reduced-dimensional systems. Undergraduates should register for PHYSICS 172 and graduate students for APPPHYS 272. Prerequisites: PHYSICS 170 and PHYSICS 171, or equivalents. Same as: APPPHYS 272

**PHYSICS 182. Quantum Gases. 3 Units.**

Introduction to the physics of quantum gases and their use in quantum simulation and computation. Topics in modern atomic physics and quantum optics will be covered, including laser cooling and trapping, ultracold collisions, optical lattices, ion traps, cavity QED, quantum phase transitions in quantum gases and lattices, BEC and quantum degenerate Fermi gases, 1D and 2D quantum gases, dipolar gases, and quantum nonequilibrium dynamics and phase transitions. Prerequisites: undergraduate quantum and statistical mechanics courses. Applied Physics 203 strongly recommended but not required. Same as: APPPHYS 282, PHYSICS 282

**PHYSICS 18N. Frontiers in Theoretical Physics and Cosmology. 3 Units.**

Preference to freshmen. The course will begin with a description of the current standard models of gravitation, cosmology, and elementary particle physics. We will then focus on frontiers of current understanding including investigations of very early universe cosmology, string theory, and the physics of black holes.

**PHYSICS 19. How Things Work: An Introduction to Physics. 3 Units.**

Introduction to the principles of physics through familiar objects and phenomena, including airplanes, cameras, computers, engines, refrigerators, lightning, radio, microwave ovens, and fluorescent lights. Estimates of real quantities from simple calculations. Prerequisite: high school algebra and trigonometry.

**PHYSICS 190. Independent Research and Study. 1-9 Unit.**

Undergraduate research in experimental or theoretical physics under the supervision of a faculty member. Prerequisites: superior work as an undergraduate Physics major and consent of instructor.

**PHYSICS 191. Scientific Communication in Physics. 3 Units.**

Development and practice of effective scientific communication in physics, including scientific publications, research proposals, science writing for a general audience, and effective communication of data. The course will involve extensive writing, reviewing, and revision, including responding effectively to critiques. Satisfies the WIM requirement for Physics and Engineering Physics majors. Intended for juniors and seniors. Prerequisites: two years of college level physics (e.g., completion of Physics 121).

**PHYSICS 198. Learning Assistant Training Seminar. 1 Unit.**

Training seminar for undergraduate students selected for the Learning Assistant (LA) program. In this seminar LAs learn and practice pedagogical techniques they will apply in an active learning classroom. LAs practice instruction strategies in a collaborative small group setting, with regular reflection and feedback. In addition, LAs learn mentoring practices to help fellow undergraduates develop academic skills. The seminar meets 90 minutes weekly with additional readings and reflection outside of class.

**PHYSICS 199. The Physics of Energy and Climate Change. 3 Units.**

Topics include measurements of temperature and sea level changes in the climate record of the Earth, satellite atmospheric spectroscopy, satellite gravity geodesy measurements of changes in water aquifers and glaciers, and ocean changes. The difference between weather fluctuations changes and climate change, climate models and their uncertainties in the context of physical, chemical and biological feedback mechanisms to changes in greenhouse gases and solar insolation will be discussed. Energy efficiency, transmission and distribution of electricity, energy storage, and the physics of harnessing fossil, wind, solar, geothermal, fission and fusion will be covered, along with prospects of future technological developments in energy use and production. Prerequisite: Physics 40 or Physics 60 series.

Same as: PHYSICS 201

**PHYSICS 201. The Physics of Energy and Climate Change. 3 Units.**

Topics include measurements of temperature and sea level changes in the climate record of the Earth, satellite atmospheric spectroscopy, satellite gravity geodesy measurements of changes in water aquifers and glaciers, and ocean changes. The difference between weather fluctuations changes and climate change, climate models and their uncertainties in the context of physical, chemical and biological feedback mechanisms to changes in greenhouse gases and solar insolation will be discussed. Energy efficiency, transmission and distribution of electricity, energy storage, and the physics of harnessing fossil, wind, solar, geothermal, fission and fusion will be covered, along with prospects of future technological developments in energy use and production. Prerequisite: Physics 40 or Physics 60 series.

Same as: PHYSICS 199

**PHYSICS 205. Senior Thesis Research. 1-12 Unit.**

Long-term experimental or theoretical project and thesis in Physics under supervision of a faculty member. Planning of the thesis project is recommended to begin as early as middle of the junior year. Successful completion of a senior thesis requires a minimum of 3 units for a letter grade completed during the senior year, along with the other formal thesis and physics major requirements. Students doing research for credit prior to senior year should sign up for Physics 190. Prerequisites: superior work as an undergraduate Physics major and approval of the thesis application.

**PHYSICS 21. Mechanics, Fluids, and Heat. 4 Units.**

How are the motions of objects and the behavior of fluids and gases determined by the laws of physics? Students learn to describe the motion of objects (kinematics) and understand why objects move as they do (dynamics). Emphasis on how Newton's three laws of motion are applied to solids, liquids, and gases to describe diverse phenomena. Understanding many-particle systems requires connecting macroscopic properties (e.g., temperature and pressure) to microscopic dynamics (collisions of particles). Laws of thermodynamics provide understanding of real-world phenomena such as energy conversion. Everyday examples are analyzed using tools of algebra and trigonometry. Problem-solving skills are developed, including verifying that derived results satisfy criteria for correctness, such as dimensional consistency and expected behavior in limiting cases. Physical understanding fostered by peer interaction and interactive group problem solving. Prerequisite: high school algebra and trigonometry; calculus not required. Autumn 2020-21: Class will be taught remote synchronously in active learning format with much of the learning in smaller breakout rooms that will not be recorded. Please enroll in a section that you can attend regularly.

**PHYSICS 210. Advanced Mechanics. 3-4 Units.**

Lagrangian and Hamiltonian mechanics. Principle of least action, Euler-Lagrange equations. Small oscillations and beyond. Symmetries, canonical transformations, Hamilton-Jacobi theory, action-angle variables. Introduction to classical field theory. Selected other topics, including nonlinear dynamical systems, attractors, chaotic motion. Undergraduates register for Physics 110 (4 units). Graduates register for Physics 210 (3 units). Prerequisites: MATH 131P or PHYSICS 111. Recommended prerequisite: PHYSICS 130. Same as: PHYSICS 110

**PHYSICS 211. Continuum Mechanics. 3 Units.**

Elasticity, fluids, turbulence, waves, gas dynamics, shocks, and MHD plasmas. Examples from everyday phenomena, geophysics, and astrophysics.

**PHYSICS 212. Statistical Mechanics. 3 Units.**

Principles, ensembles, statistical equilibrium. Thermodynamic functions, ideal and near-ideal gases. Fluctuations. Mean-field description of phase transitions and associated critical exponents. One-dimensional Ising model and other exact solutions. Renormalization and scaling relations. Prerequisites: PHYSICS 131, 171, or equivalents.

**PHYSICS 216. Back of the Envelope Physics. 2 Units.**

This course will deal with order of magnitude or approximate, low-tech approaches to estimating physical effects in various systems. One goal is to promote a synthesis of understanding of basic physics (including quantum mechanics, electromagnetism, and physics of fluids) through solving various classic problems. A special feature of the class this year will be a new format, where students will develop and present many of the lectures in close consultation with the faculty instructor. This is intended to both enhance learning, and to keep the interactive nature of instruction front and center in a quarter where lectures are delivered over zoom.

**PHYSICS 21S. Mechanics and Heat. 5 Units.**

How are the motions of objects and the behavior of fluids and gases determined by the laws of physics? Students learn to describe the motion of objects (kinematics) and understand why objects move as they do (dynamics). Emphasis on how Newton's three laws of motion are applied to solids, liquids, and gases to describe phenomena as diverse as spinning gymnasts, blood flow, and sound waves. Understanding many-particle systems requires connecting macroscopic properties (e.g., temperature and pressure) to microscopic dynamics (collisions of particles). Laws of thermodynamics provide understanding of real-world phenomena such as energy conversion and performance limits of heat engines. Everyday examples are analyzed using tools of algebra and trigonometry. Problem-solving skills are developed, including verifying that derived results satisfy criteria for correctness, such as dimensional consistency and expected behavior in limiting cases. Physical understanding fostered by peer interaction and demonstrations in lecture, and interactive group problem solving in discussion sections. Prerequisite: high school algebra and trigonometry; calculus not required.

**PHYSICS 22. Mechanics, Fluids, and Heat Laboratory. 1 Unit.**

Guided hands-on exploration of concepts in classical mechanics, fluids, and thermodynamics with an emphasis on student predictions, observations and explanations. Pre- or corequisite: PHYSICS 21. In this unusual pandemic year we have planned remote lab activity for you. These labs are a mix of online labs as well as hands-on exercises you can do at home, in a dorm or wherever you may be. The class will be structured with an online Zoom section, where you and others in your section will meet with a TA and go over your results, and do some group exercises. You can do the online materials with a virtual lab partner, we encourage you to get the benefit of someone to collaborate on your analysis and observations. We will be sending every enrolled student a kit of hands-on lab materials, you will get more details the first week of class.

**PHYSICS 220. Classical Electrodynamics. 3 Units.**

Special relativity: The principles of relativity, Lorentz transformations, four vectors and tensors, relativistic mechanics and the principle of least action. Lagrangian formulation, charges in electromagnetic fields, gauge invariance, the electromagnetic field tensor, covariant equations of electrodynamics and mechanics, four-current and continuity equation. Noether's theorem and conservation laws, Poynting's theorem, stress-energy tensor. Constant electromagnetic fields: conductors and dielectrics, magnetic media, electric and magnetic forces, and energy. Electromagnetic waves: Plane and monochromatic waves, spectral resolution, polarization, electromagnetic properties of matter, dispersion relations, wave guides and cavities. Prerequisites: PHYSICS 121 and PHYSICS 210, or equivalent; MATH 106 or MATH 116, and MATH 132 or equivalent.

**PHYSICS 223. Stochastic and Nonlinear Dynamics. 3 Units.**

Theoretical analysis of dynamical processes: dynamical systems, stochastic processes, and spatiotemporal dynamics. Motivations and applications from biology and physics. Emphasis is on methods including qualitative approaches, asymptotics, and multiple scale analysis. Prerequisites: ordinary and partial differential equations, complex analysis, and probability or statistical physics. Same as: APPPHYS 223, BIO 223, BIOE 213

**PHYSICS 23. Electricity, Magnetism, and Optics. 4 Units.**

How are electric and magnetic fields generated by static and moving charges, and what are their applications? How is light related to electromagnetic waves? Students learn to represent and analyze electric and magnetic fields to understand electric circuits, motors, and generators. The wave nature of light is used to explain interference, diffraction, and polarization phenomena. Geometric optics is employed to understand how lenses and mirrors form images. These descriptions are combined to understand the workings and limitations of optical systems such as the eye, corrective vision, cameras, telescopes, and microscopes. Discussions based on the language of algebra and trigonometry. Physical understanding fostered by peer interaction and demonstrations in lecture, and interactive group problem solving in discussion sections. Prerequisite: PHYSICS 21 or PHYSICS 21S.

**PHYSICS 230. Graduate Quantum Mechanics I. 3 Units.**

Fundamental concepts. Introduction to Hilbert spaces and Dirac's notation. Postulates applied to simple systems, including those with periodic structure. Symmetry operations and gauge transformation. The path integral formulation of quantum statistical mechanics. Problems related to measurement theory. The quantum theory of angular momenta and central potential problems. Prerequisite: PHYSICS 131 or equivalent.

**PHYSICS 231. Graduate Quantum Mechanics II. 3 Units.**

Basis for higher level courses on atomic solid state and particle physics. Problems related to measurement theory and introduction to quantum computing. Approximation methods for time-independent and time-dependent perturbations. Semiclassical and quantum theory of radiation, second quantization of radiation and matter fields. Systems of identical particles and many electron atoms and molecules. Prerequisite: PHYSICS 230.

**PHYSICS 234. Advanced Topics in Quantum Mechanics. 3-4 Units.**

Scattering theory, partial wave expansion, Born approximation. Additional topics may include nature of quantum measurement, EPR paradox, Bell's inequality, and topics in quantum information science; path integrals and applications; Berry's phase; structure of multi-electron atoms (Hartree-Fock); relativistic quantum mechanics (Dirac equation). Undergraduates register for PHYSICS 134 (4 units). Graduate students register for PHYSICS 234 (3 units). Prerequisite: PHYSICS 131. Same as: PHYSICS 134

**PHYSICS 23S. Electricity and Optics. 5 Units.**

How are electric and magnetic fields generated by static and moving charges, and what are their applications? How is light related to electromagnetic waves? Students learn to represent and analyze electric and magnetic fields to understand electric circuits, motors, and generators. The wave nature of light is used to explain interference, diffraction, and polarization phenomena. Geometric optics is employed to understand how lenses and mirrors form images. These descriptions are combined to understand the workings and limitations of optical systems such as the eye, corrective vision, cameras, telescopes, and microscopes. Discussions based on the language of algebra and trigonometry. Physical understanding fostered by peer interaction and demonstrations in lecture, and interactive group problem solving in discussion sections. Prerequisite: PHYSICS 21 or PHYSICS 21S.

**PHYSICS 24. Electricity, Magnetism, and Optics Laboratory. 1 Unit.**

Guided hands-on exploration of concepts in electricity and magnetism, circuits and optics with an emphasis on student predictions, observations and explanations. Introduction to multimeters and oscilloscopes. Pre- or corequisite: PHYS 23.

**PHYSICS 240. Introduction to the Physics of Energy. 3 Units.**

Energy as a consumable. Forms and interconvertability. World Joule budget. Equivalents in rivers, oil pipelines and nuclear weapons. Quantum mechanics of fire, batteries and fuel cells. Hydrocarbon and hydrogen synthesis. Fundamental limits to mechanical, electrical and magnetic strengths of materials. Flywheels, capacitors and high pressure tanks. Principles of AC and DC power transmission. Impossibility of pure electricity storage. Surge and peaking. Solar constant. Photovoltaic and thermal solar conversion. Physical limits on agriculture.

**PHYSICS 241. Introduction to Nuclear Energy. 3 Units.**

Radioactivity. Elementary nuclear processes. Energetics of fission and fusion. Cross-sections and resonances. Fissionable and fertile isotopes. Neutron budgets. Light water, heavy water and graphite reactors. World nuclear energy production. World reserves of uranium and thorium. Plutonium, reprocessing and proliferation. Half lives of fission decay products and actinides made by neutron capture. Nuclear waste. Three Mile Island and Chernobyl. Molten sodium breeders. Generation-IV reactors. Inertial confinement and magnetic fusion. Laser compression. Fast neutron production and fission-fusion hybrids. Prerequisites: Strong undergraduate background in elementary chemistry and physics. PHYSICS 240 and PHYSICS 252 recommended but not required. Interested undergraduates encouraged to enroll, with permission of instructor.

**PHYSICS 25. Modern Physics. 4 Units.**

How do the discoveries since the dawn of the 20th century impact our understanding of 21st-century physics? This course introduces the foundations of modern physics: Einstein's theory of special relativity and quantum mechanics. Combining the language of physics with tools from algebra and trigonometry, students gain insights into how the universe works on both the smallest and largest scales. Topics may include atomic, molecular, and laser physics; semiconductors; elementary particles and the fundamental forces; nuclear physics (fission, fusion, and radioactivity); astrophysics and cosmology (the contents and evolution of the universe). Emphasis on applications of modern physics in everyday life, progress made in our understanding of the universe, and open questions that are the subject of active research. Physical understanding fostered by peer interaction and demonstrations in lecture, and interactive group problem solving in discussion sections. Prerequisite: PHYSICS 23 or PHYSICS 23S.

**PHYSICS 252. Introduction to Particle Physics I. 3 Units.**

Elementary particles and the fundamental forces. Quarks and leptons. The mediators of the electromagnetic, weak and strong interactions. Interaction of particles with matter; particle acceleration, and detection techniques. Symmetries and conservation laws. Bound states. Decay rates. Cross sections. Feynman diagrams. Introduction to Feynman integrals. The Dirac equation. Feynman rules for quantum electrodynamics and for chromodynamics. Undergraduates register for PHYSICS 152. Graduate students register for PHYSICS 252. (Graduate students will be required to complete additional assignments in a format determined by the instructor.) Prerequisite: PHYSICS 130. Pre- or corequisite: PHYSICS 131. Same as: PHYSICS 152

**PHYSICS 26. Modern Physics Laboratory. 1 Unit.**

Guided hands-on and simulation-based exploration of concepts in modern physics, including special relativity, quantum mechanics and nuclear physics with an emphasis on student predictions, observations and explanations. Pre- or corequisite: PHYSICS 25.

**PHYSICS 260. Introduction to Stellar and Galactic Astrophysics. 3 Units.**

Radiative processes. Observed characteristics of stars and the Milky Way galaxy. Physical processes in stars and matter under extreme conditions. Structure and evolution of stars from birth to death. White dwarfs, planetary nebulae, supernovae, neutron stars, pulsars, binary stars, x-ray stars, and black holes. Galactic structure, interstellar medium, molecular clouds, HI and HII regions, star formation, and element abundances. Undergraduates register for PHYSICS 160. Graduate students register for PHYSICS 260. Pre-requisite: Physics 120 or permission of instructor. Recommended: Some familiarity with plotting and basic numerical calculations.

Same as: PHYSICS 160

**PHYSICS 261. Introduction to Cosmology and Extragalactic Astrophysics. 3 Units.**

What do we know about the physical origins, content, and evolution of the Universe – and how do we know it? Students learn how cosmological distances and times, and the geometry and expansion of space, are described and measured. Composition of the Universe. Origin of matter and the elements. Observational evidence for dark matter and dark energy. Thermal history of the Universe, from inflation to the present. Emergence of large-scale structure from quantum perturbations in the early Universe. Astrophysical tools used to learn about the Universe. Big open questions in cosmology. Undergraduates register for Physics 161. Graduates register for Physics 261. (Graduate students will be required to complete additional assignments in a format determined by the instructor.) Prerequisite: PHYSICS 121 or equivalent.

Same as: PHYSICS 161

**PHYSICS 262. General Relativity. 3 Units.**

Einstein's General Theory of Relativity is a basis for modern ideas of fundamental physics, including string theory, as well as for studies of cosmology and astrophysics. The course begins with an overview of special relativity, and the description of gravity as arising from curved space. From Riemannian geometry and the geodesic equations, to curvature, the energy-momentum tensor, and the Einstein field equations. Applications of General Relativity: topics may include experimental tests of General Relativity and the weak-field limit, black holes (Schwarzschild, charged Reissner-Nordstrom, and rotating Kerr black holes), gravitational waves (including detection methods), and an introduction to cosmology (including cosmic microwave background radiation, dark energy, and experimental probes). Prerequisite: PHYSICS 121 or equivalent including special relativity.

**PHYSICS 266. Statistical Methods in Experimental Physics. 3 Units.**

Statistical methods constitute a fundamental tool for the analysis and interpretation of experimental physics data. In this course, students will learn the foundations of statistical data analysis methods and how to apply them to the analysis of experimental data. Problem sets will include data-sets from real experiments and require the use of programming tools to extract physics results. Topics include probability and statistics, experimental uncertainties, parameter estimation, confidence limits, and hypothesis testing. Students will be required to complete a final project. Same as: PHYSICS 166

**PHYSICS 268. Physics with Neutrinos. 3 Units.**

Relativistic fermions, Weyl and Dirac equations, Majorana masses. Electroweak theory, neutrino cross sections, neutrino refraction in matter, MSW effect. Three-flavor oscillations, charge-parity violation, searches for sterile neutrinos, modern long- and short-baseline oscillation experiments. Seesaw mechanism, models of neutrino masses, lepton flavor violation. Neutrinoless double beta decay. Cosmological constraints on neutrino properties. Advanced topics, such as collective oscillations in supernovae or ultrahigh energy neutrinos, offered as optional projects. The material in this course is largely complementary to PHYS 269, focusing on particle physics aspects of neutrinos. Prerequisites: PHYSICS 121, 131 and 171 or equivalent. PHYS 230-231, 269, 152 and 161 or equivalent are helpful, but not required.

**PHYSICS 269. Neutrinos in Astrophysics and Cosmology. 3 Units.**

Basic neutrino properties. Flavor evolution in vacuum and in matter. Oscillations of atmospheric, reactor and beam neutrinos. Measurements of solar neutrinos; physics of level-crossing and the resolution of the solar neutrino problem. Roles of neutrinos in stellar evolution; bounds from stellar cooling. Neutrinos and stellar collapse; energy transport, collective flavor oscillations, neutrino flavor in turbulent medium. Ultra-high-energy neutrinos. The cosmic neutrino background, its impact on the cosmic microwave background and structure formation; cosmological bounds on the neutrino sector. Prerequisites/corequisites: PHYSICS 121, 131 and 171 or equivalent. PHYS 230-231, 152 and 161 or equivalent are helpful, but not required. May be repeat for credit.

**PHYSICS 275. Electrons in Nanostructures. 3 Units.**

The strange behavior of electrons in metals or semiconductors at length scales below 1 micron, smaller than familiar macroscopic objects but larger than atoms. Ballistic transport, Coulomb blockade, localization, quantum mechanical interference, persistent currents, graphene, topological insulators, 1D wires. After a few background lectures, students come to each class session prepared to discuss one or more classic review articles or recent experimental publications. Prerequisite: undergraduate quantum mechanics and solid state physics preferred; physicists, engineers, chemists welcome.

**PHYSICS 282. Quantum Gases. 3 Units.**

Introduction to the physics of quantum gases and their use in quantum simulation and computation. Topics in modern atomic physics and quantum optics will be covered, including laser cooling and trapping, ultracold collisions, optical lattices, ion traps, cavity QED, quantum phase transitions in quantum gases and lattices, BEC and quantum degenerate Fermi gases, 1D and 2D quantum gases, dipolar gases, and quantum nonequilibrium dynamics and phase transitions. Prerequisites: undergraduate quantum and statistical mechanics courses. Applied Physics 203 strongly recommended but not required. Same as: APPPHYS 282, PHYSICS 182

**PHYSICS 290. Research Activities at Stanford. 1 Unit.**

Required of first-year Physics graduate students; suggested for junior or senior Physics majors for 1 unit. Review of research activities in the department and elsewhere at Stanford at a level suitable for entering graduate students.

**PHYSICS 291. Curricular Practical Training. 1-3 Unit.**

Curricular practical training for students participating in an internship with a physics-related focus. Meets the requirements for curricular practical training for students on F-1 visas. Prior to the internship, students submit a concise description of the proposed project and work activities. After the internship, students submit a summary of the work completed and skills learned, including a reflection on the professional growth gained as a result of the internship. This course may be repeated for credit. Students are responsible for arranging their own internship/employment and faculty sponsorship. Register under faculty sponsor's section number.

**PHYSICS 293. Literature of Physics. 1-15 Unit.**

Study of the literature of any special topic. Preparation, presentation of reports. If taken under the supervision of a faculty member outside the department, approval of the Physics chair required. Prerequisites: 25 units of college physics, consent of instructor.

**PHYSICS 294. Teaching of Physics Seminar. 1 Unit.**

Weekly seminar/discussions on interactive techniques for teaching physics. Practicum which includes class observations, grading and student teaching in current courses. Required of all Teaching Assistants prior to first teaching assignment. Mandatory attendance at weekly in-class sessions during first 5 weeks of the quarter; mandatory successful completion of all practicum activities. Students who do not hold a US Passport must complete the International Teaching/Course Assistant Screening Exam and be cleared to TA before taking the class. Details: <https://language.stanford.edu/programs/efs/languages/english-foreign-students/international-teachingcourse-assistant-screening>. Enrollment in PHYSICS 294 is by permission. To get a permission number please complete form: [https://stanforduniversity.qualtrics.com/jfe/form/SV\\_7VVM88d1iMTw8Xr](https://stanforduniversity.qualtrics.com/jfe/form/SV_7VVM88d1iMTw8Xr). If you have not heard from us by the beginning of class, please come to the first class session.

**PHYSICS 295. Learning & Teaching of Science. 3 Units.**

This course will provide students with a basic knowledge of the relevant research in cognitive psychology and science education and the ability to apply that knowledge to enhance their ability to learn and teach science, particularly at the undergraduate level. Course will involve readings, discussion, and application of the ideas through creation of learning activities. It is suitable for advanced undergraduates and graduate students with some science background.

Same as: EDUC 280, ENGR 295, MED 270, VPTL 280

**PHYSICS 301. Astrophysics Laboratory. 3 Units.**

Designed for physics graduate students but open to all graduate students with a calculus-based physics background and some laboratory and coding experience. Students make and analyze observations using the telescopes at the Stanford Student Observatory. Topics covered include navigating the night sky, the physics of stars and galaxies, telescope instrumentation and operation, imaging and spectroscopic techniques, quantitative error analysis, and effective scientific communication. The course concludes with an independent project where student teams propose and execute an observational astronomy project of their choosing, using techniques learned in class to gather and analyze their data, and presenting their findings in the forms of professional-style oral presentations and research papers. Enrollment by permission. To get a permission number please complete form: <http://web.stanford.edu/~elva/physics301prelim.fb> If you have not heard from us by the beginning of class, please come to the first class session.

**PHYSICS 312. Basic Plasma Physics. 3 Units.**

For the nonspecialist who needs a working knowledge of plasma physics for space science, astrophysics, fusion, or laser applications. Topics: orbit theory, the Boltzmann equation, fluid equations, magneto hydrodynamics (MHD) waves and instabilities, electromagnetic (EM) waves, the Vlasov theory of electrostatic (ES) waves and instabilities including Landau damping and quasilinear theory, the Fokker-Planck equation, and relaxation processes. Advanced topics in resistive instabilities and particle acceleration. Prerequisite: PHYSICS 220, or consent of instructor.

**PHYSICS 321. Laser Spectroscopy. 3 Units.**

Theoretical concepts and experimental techniques. Absorption, dispersion, Kramers-Kronig relations, line-shapes. Classical and laser linear spectroscopy. Semiclassical theory of laser atom interaction: time-dependent perturbation theory, density matrix, optical Bloch equations, coherent pulse propagation, multiphoton transitions. High-resolution nonlinear laser spectroscopy: saturation spectroscopy, polarization spectroscopy, two-photon and multiphoton spectroscopy, optical Ramsey spectroscopy. Phase conjugation. Four-wave mixing, harmonic generation. Coherent Raman spectroscopy, quantum beats, ultra-sensitive detection. Prerequisite: PHYSICS 230. Recommended: PHYSICS 231.

**PHYSICS 330. Quantum Field Theory I. 3 Units.**

Lorentz Invariance. S-Matrix. Quantization of scalar and Dirac fields. Feynman diagrams. Quantum electrodynamics. Elementary electrodynamic processes: Compton scattering; e-e- annihilation. Loop diagrams. Prerequisites: PHYSICS 130, PHYSICS 131, or equivalents AND a basic knowledge of Group Theory.

**PHYSICS 331. Quantum Field Theory II. 3 Units.**

Functional integral methods. Local gauge invariance and Yang-Mills fields. Asymptotic freedom. Spontaneous symmetry breaking and the Higgs mechanism. Unified models of weak and electromagnetic interactions. Prerequisite: PHYSICS 330.

**PHYSICS 332. Quantum Field Theory III. 3 Units.**

Theory of renormalization. The renormalization group and applications to the theory of phase transitions. Renormalization of Yang-Mills theories. Applications of the renormalization group of quantum chromodynamics. Perturbation theory anomalies. Applications to particle phenomenology. Prerequisite: PHYSICS 331.

**PHYSICS 351. Standard Model of Particle Physics. 3 Units.**

Symmetries, group theory, gauge invariance, Lagrangian of the Standard Model, flavor group, flavor-changing neutral currents, CKM quark mixing matrix, GIM mechanism, rare processes, neutrino masses, seesaw mechanism, QCD confinement and chiral symmetry breaking, instantons, strong CP problem, QCD axion. Prerequisite: PHYSICS 330.

**PHYSICS 360. Modern Astrophysics. 3 Units.**

Basic theory of production of radiation in stars, galaxies and diffuse interstellar and intergalactic media and transfer of radiation throughout the universe. Magnetic fields, turbulence shocks and particle acceleration and transport around magnetospheres of planets to clusters of galaxies. Application to compact objects, pulsars and accretion in binary stars and super-massive black holes, supernova remnants, cosmic rays and active galactic nuclei. Prerequisite: PHYSICS 260 or equivalent.

**PHYSICS 361. Cosmology and Extragalactic Astrophysics. 3 Units.**

Intended as a complement to Ph 362 and Ph 364. Galaxies (including their nuclei), clusters, stars and backgrounds in the contemporary universe. Geometry, kinematics, dynamics, and physics of the universe at large. Evolution of the universe following the epoch of nucleosynthesis. Epochs of recombination, reionization and first galaxy formation. Fluid and kinetic description of the growth of structure with application to microwave background fluctuations and galaxy surveys. Gravitational lensing. The course will feature interleaved discussion of theory and observation. Undergraduate exposure to general relativity and cosmology at the level of Ph 262 and Ph 161 will be helpful but is not essential.

**PHYSICS 362. The Early Universe. 3 Units.**

Intended to complement PHYSICS 361, this course will cover the earlier period in cosmology up to and including nucleosynthesis. The focus will be on high energy, early universe physics. This includes topics such as inflation and reheating including generation of density perturbations and primordial gravitational waves, baryogenesis mechanisms, out of equilibrium particle production processes in the early universe e.g. both thermal and non-thermal production mechanisms for dark matter candidates such as WIMPs and axions, and production of the light nuclei and neutrinos. Techniques covered include for example out of equilibrium statistical mechanics such as the Boltzmann equation, and dynamics of scalar fields in the expanding universe. Other possible topics if time permits may include cosmological phase transitions and objects such as monopoles and primordial black holes. We will use quantum field theory, although it will hopefully be accessible for those without much background in that area. Suggested prerequisites: general relativity at the level of PHYSICS 262, some knowledge of cosmology and in particular the basics of FRW cosmology as in PHYSICS 361 for example, and some knowledge of quantum field theory e.g. at the level of PHYSICS 331 as a corequisite.

**PHYSICS 364. Gravitational Radiation, Black Holes and Neutron Stars. 3 Units.**

General relativistic theory of spinning black holes and neutron stars including accretion, jets and tidal capture. Direct and indirect observation of relativistic effects in active galactic nuclei and stellar sources. Linear theory of the generation and propagation of (non-primordial) gravitational radiation. Detection of gravitational waves by Michelson interferometers, pulsars and atom interferometers. Nonlinear emission by binary black holes. Nuclear equation of state and nucleosynthetic implications of neutron star binaries. Pre-requisite: Ph 262 or equivalent.

**PHYSICS 366. Statistical Methods in Astrophysics. 3 Units.**

Foundations of principled inference from data, primarily in the Bayesian framework, organized around applications in astrophysics and cosmology. Topics include probabilistic modeling of data, parameter constraints and model comparison, numerical methods including Markov Chain Monte Carlo, and connections to frequentist and machine learning frameworks. The course is organized around tutorials and a final project, providing hands-on experience with real data. Prerequisite: programming in Python or a similar language at the level of CS 106A. Recommended but not required: probability at the level of STATS 116 or PHYSICS 166/266.

**PHYSICS 367. Special Topics in Astrophysics: Structure Formation and Galaxy Formation. 2 Units.**

How does structure form in the Universe, and how do galaxies form within that structure? Topics will include the dependence of structure formation on cosmological parameters and the nature of dark matter, the key astrophysical processes involved in galaxy formation, and the connection between matter and galaxies. Current outstanding problems in structure formation and galaxy formation and the modern techniques used to address them will be highlighted. Course will include reading current literature and hands on computational problems. Recommended prerequisite: PHYSICS 261 or equivalent.

**PHYSICS 368. Computational Cosmology and Astrophysics. 2 Units.**

Create virtual Universes and understand our own using your computer. Techniques for studying the dynamics of dark matter and gas as it assembles over cosmic time to form the structure in the Universe. The use of modern computer codes on supercomputers to combine modeling of gravitation, gas dynamics, radiation processes, magnetohydrodynamics, and other relevant physical processes to make detailed predictions about the evolution of the Universe. Practical exercises to explore how cosmic microwave background observations are sensitive to cosmological parameters, how key numerical algorithms work, how different cosmological observations can be combined to constrain what the Universe is made of and how it changed over time. Additional current topics in computational cosmology depending on student interest. Hands-on activities based on open-source software in C++ and Python. Pre- or corequisites: PHYSICS 361. Recommended prerequisite: PHYSICS 366.

**PHYSICS 372. Condensed Matter Theory I. 3 Units.**

Fermi liquid theory, many-body perturbation theory, response function, functional integrals, interaction of electrons with impurities. Prerequisite: APPPHYS 273 or equivalent.

**PHYSICS 373. Condensed Matter Theory II. 3 Units.**

Superfluidity and superconductivity. Quantum magnetism. Prerequisite: PHYSICS 372.



**PHYSICS 40. Vector and Mathematical Analysis for Mechanics. 2 Units.**

Physics 40 teaches fundamental math and physics concepts that are important for success in Physics 41+ and engineering statics/dynamics. This class has a strong emphasis on physics problem solving schema and vector and mathematical analysis for geometry, forces, and motion. Students master both geometric and algebraic representations of vectors, resolving vectors into components, vector addition/subtraction, dot-products, cross-products, and derivatives. Through systematic practice, students translate between various representations, e.g. sketches, descriptions of a physical system, equations, graphs, and real systems (from various physics and engineering disciplines). Vector equations are used to generate scalar equations, which are then solved using analytical or easy-to-use online tools. Physics 40 is an on-ramp to Physics 41 for students with little high school physics. The minimum corequisite is Math 20 (or equivalent). A permission number is required to enroll. Contact [mitiguy@stanford.edu](mailto:mitiguy@stanford.edu).

**PHYSICS 41. Mechanics. 4 Units.**

How are motions of objects in the physical world determined by laws of physics? Students learn to describe the motion of objects (kinematics) and then understand why motions have the form they do (dynamics). Emphasis on how the important physical principles in mechanics, such as conservation of momentum and energy for translational and rotational motion, follow from just three laws of nature: Newton's laws of motion. Distinction made between fundamental laws of nature and empirical rules that are useful approximations for more complex physics. Problems drawn from examples of mechanics in everyday life. Skills developed in verifying that derived results satisfy criteria for correctness, such as dimensional consistency and expected behavior in limiting cases. Discussions based on language of mathematics, particularly vector representations and operations, and calculus. Physical understanding fostered by peer interaction and demonstrations in lecture, and discussion sections based on interactive group problem solving. Spring 2020-21: Class will be taught remote synchronously in active learning format with much of the learning in smaller breakout rooms so class will not be recorded. Please enroll in a section that you can attend regularly. In order to register for this class all FROSH must complete the Physics Placement Diagnostic at <https://physics.stanford.edu/academics/undergraduate-students/placement-diagnostic>. Students who complete the Physics Placement Diagnostic by 3 PM (Pacific) on Friday will have their hold lifted over the weekend. Minimum prerequisites: High school physics and MATH 20 (or high school calculus if sufficiently rigorous). Minimum co-requisite: MATH 21 or equivalent. Since high school math classes vary widely, it is recommended that you take at least one math class at Stanford before or concurrently with taking Physics 41. In addition, it is recommended that you take Math 51 or CME 100 before taking the next course in the Physics 40 series, Physics 43.

**PHYSICS 41E. Mechanics, Concepts, Calculations, and Context. 5 Units.**

Physics 41E (Physics 41 Extended) is an 5-unit version of Physics 41 (4 units) for students with little or no high school physics or calculus. Course topics and mathematical complexity are identical to Physics 41, but the extra classroom time allows students to engage with concepts, develop problem solving skills, and become fluent in mathematical tools that include vector representations and operations, and calculus. The course will use problems drawn from everyday life to explore important physical principles in mechanics, such as Newton's Laws of motion, equations of kinematics, and conservation of energy and momentum. Prerequisite: Math 19 or equivalent; Co-requisite: Math 20 or equivalent. In order to register for this class students must EITHER have already taken an introductory Physics class (20, 40, or 60 sequence) or have taken the Physics Placement Diagnostic at <https://physics.stanford.edu/academics/undergraduate-students/placement-diagnostic>. Enrollment is via permission number which can be obtained by filling in the application at [https://stanforduniversity.qualtrics.com/jfe/form/SV\\_2fNzeSIjoYtKiln](https://stanforduniversity.qualtrics.com/jfe/form/SV_2fNzeSIjoYtKiln).

**PHYSICS 42. Classical Mechanics Laboratory. 1 Unit.**

Hands-on exploration of concepts in classical mechanics: Newton's laws, conservation laws, rotational motion. Introduction to laboratory techniques, experimental equipment and data analysis. Pre- or corequisite: PHYSICS 41. In this unusual pandemic year we have planned remote lab activity for you. These labs are a mix of online labs as well as hands-on exercises you can do at home, in a dorm or wherever you may be. The class will be structured with an online Zoom section, where you and others in your section will meet with a TA and go over your results, and do some group exercises. You can do the online materials with a virtual lab partner, we encourage you to get the benefit of someone to collaborate on your analysis and observations. We will be sending every enrolled student a kit of hands-on lab materials, you will get more details the first week of class.

**PHYSICS 43. Electricity and Magnetism. 4 Units.**

What is electricity? What is magnetism? How are they related? How do these phenomena manifest themselves in the physical world? The theory of electricity and magnetism, as codified by Maxwell's equations, underlies much of the observable universe. Students develop both conceptual and quantitative knowledge of this theory. Topics include: electrostatics; magnetostatics; simple AC and DC circuits involving capacitors, inductors, and resistors; integral form of Maxwell's equations; electromagnetic waves. Principles illustrated in the context of modern technologies. Broader scientific questions addressed include: How do physical theories evolve? What is the interplay between basic physical theories and associated technologies? Discussions based on the language of mathematics, particularly differential and integral calculus, and vectors. Physical understanding fostered by peer interaction and demonstrations in lecture, and discussion sections based on interactive group problem solving. Prerequisite: PHYSICS 41 or equivalent. MATH 21 or MATH 51 or CME 100 or equivalent. Recommended corequisite: MATH 52 or CME 102.

**PHYSICS 43A. Electricity and Magnetism: Concepts, Calculations and Context. 1 Unit.**

Additional assistance and applications for Physics 43. In-class problems in physics and engineering. Exercises in calculations of electric and magnetic forces and field to reinforce concepts and techniques; Calculations involving inductors, transformers, AC circuits, motors and generators. Highly recommended for students with limited or no high school physics or calculus. Corequisite: PHYSICS 43-34 or PHYSICS 43-35; Prerequisite: application at [https://stanforduniversity.qualtrics.com/jfe/form/SV\\_da1PUm1scvNQ5IV](https://stanforduniversity.qualtrics.com/jfe/form/SV_da1PUm1scvNQ5IV).

**PHYSICS 43N. Understanding Electromagnetic Phenomena. 1 Unit.**

Preference to freshmen. Expands on the material presented in PHYSICS 43; applications of concepts in electricity and magnetism to everyday phenomena and to topics in current physics research. Corequisite: PHYSICS 43 or advanced placement.

**PHYSICS 44. Electricity and Magnetism Lab. 1 Unit.**

Hands-on exploration of concepts in electricity, magnetism, and circuits. Introduction to multimeters, function generators, oscilloscopes, and graphing techniques. Pre- or corequisite: PHYSICS 43.

**PHYSICS 45. Light and Heat. 4 Units.**

What is temperature? How do the elementary processes of mechanics, which are intrinsically reversible, result in phenomena that are clearly irreversible when applied to a very large number of particles, the ultimate example being life? In thermodynamics, students discover that the approach of classical mechanics is not sufficient to deal with the extremely large number of particles present in a macroscopic amount of gas. The paradigm of thermodynamics leads to a deeper understanding of real-world phenomena such as energy conversion and the performance limits of thermal engines. In optics, students see how a geometrical approach allows the design of optical systems based on reflection and refraction, while the wave nature of light leads to interference phenomena. The two approaches come together in understanding the diffraction limit of microscopes and telescopes. Discussions based on the language of mathematics, particularly calculus. Physical understanding fostered by peer interaction and demonstrations in lecture, and discussion sections based on interactive group problem solving. In order to register for this class students must EITHER have already taken an introductory Physics class (20, 40, or 60 sequence) or have taken the Physics Placement Diagnostic at <https://physics.stanford.edu/academics/undergraduate-students/placement-diagnostic>. Prerequisite: PHYSICS 41 or equivalent. MATH 21 or MATH 51 or CME 100 or equivalent.

**PHYSICS 450. Advanced Theoretical Physics I: Random Matrices in Physics. 3 Units.**

This course will survey some of the basic ideas and techniques in the theory of random matrices. These will be interspersed with discussions of some of the physical applications of these ideas including: energy spectra of quantum chaotic systems and the Eigenstate Thermalization Hypothesis; entanglement entropies; and aspects of 2D quantum gravity.

**PHYSICS 451. Advanced Theoretical Physics II: Quantum Information Theory, Complexity, Gravity and Black Holes. 3 Units.**

This course will cover the developing intersection between quantum information theory and the quantum theory of gravity. We will focus on the central roles of entanglement and computational complexity in black hole physics. Prerequisites: Basic knowledge of quantum mechanics, quantum field theory, and general relativity.

**PHYSICS 455. Introductory Seminar on Recent Developments in Theoretical Physics. 1 Unit.**

This seminar is for first-year graduate students interested in theoretical physics. It is driven by introductory-level student talks and focuses on recent foundational developments across the field. Typical areas of interest include cosmology, particle physics, string theory, quantum gravity, and condensed matter.

**PHYSICS 45N. Topics in Light and Heat. 1 Unit.**

Preference to freshmen. Explores the quantum and classical properties of light from stars, lasers and other sources. Includes modern applications ranging from gravity wave interferometers to x-ray lasers.

**PHYSICS 46. Light and Heat Laboratory. 1 Unit.**

Hands-on exploration of concepts in geometrical optics, wave optics and thermodynamics. Pre- or corequisite: PHYSICS 45. In this unusual pandemic year we have planned remote lab activity for you. These labs are a mix of online labs as well as hands-on exercises you can do at home, in a dorm or wherever you may be. The class will be structured with an online Zoom section, where you and others in your section will meet with a TA and go over your results, and do some group exercises. You can do the online materials with a virtual lab partner, we encourage you to get the benefit of someone to collaborate on your analysis and observations. We will be sending every enrolled student a kit of hands-on lab materials, you will get more details the first week of class.

**PHYSICS 470. Topics in Modern Condensed Matter Theory I: Many Body Quantum Dynamics. 3 Units.**

Many body quantum systems can display rich emergent dynamical phenomena far from thermal equilibrium, whose understanding represents an exciting frontier of research at the interface of condensed matter, statistical physics, high energy theory and quantum information. This course is intended to serve as an introduction to this active research area, assuming only a knowledge of quantum mechanics and statistical physics. Topics covered include: quantum thermalization, many-body localization, quantum entanglement and its dynamics, tensor network methods, dynamical quantum phases and phase transitions, and Floquet theory. Prerequisites: PHYSICS 113, PHYSICS 130, PHYSICS 131, PHYSICS 170, and PHYSICS 171.

**PHYSICS 471. Topics in Modern Condensed Matter Theory II: Open Problems in the theory of metals & superconductor. 3 Units.**

We will begin by reviewing a modern perspective on the theory of conventional (BCS s-wave) and unconventional (e.g. d-wave) superconductors. We will then discuss a variety of issues that are of current interest, but which are either incompletely understood or entirely open problems in the field. Depending upon the interests of the class and the whims of the instructor, topics to be covered may include: quantum superconductor to insulator and superconductor to metal transitions, emergence of superconductivity from a non-Fermi liquid normal state, exotic superconducting phases of matter, interplay between superconductivity and other broken symmetry states (issues of  $\zeta$  intertwined orders), and superconductivity in paradigmatic models of highly correlated electron systems, including problems in which there is an interplay between strong electron-electron and electron-phonon interactions. We will also touch on theoretical ideas - all of them currently still being explored and hence controversial - concerning theories of unconventional metallic states - i.e. metallic states that cannot be well described in the context of a theory of weakly interacting quasiparticles. While the subject matter of this course is motivated by ongoing experimental studies in a variety of quantum materials and devices, the principle focus of the class will be on a coherent understanding of what is known and on crisply identifying what is not known.

**PHYSICS 490. Research. 1-18 Unit.**

Open only to Physics graduate students, with consent of instructor. Work is in experimental or theoretical problems in research, as distinguished from independent study of a non-research character in 190 and 293.

**PHYSICS 491. Symmetry and Quantum Information. 2 Units.**

This course gives an introduction to quantum information theory through the study of symmetries. We start with Bell's and Tsirelson's inequalities, which bound the strength of classical and quantum correlations, and discuss their relation to algebraic symmetries. Next, we exploit permutation symmetry to quantify the monogamy of entanglement and explain how to securely distribute a secret key. Lastly, we study quantum information in the limit of many copies and discuss a powerful technique for constructing universal quantum protocols, based on the Schur-Weyl duality between the unitary and symmetric groups. Applications include quantum data compression, state estimation, and entanglement distillation. Prerequisite: PHYSICS 230 or equivalent. All required group and representation theory will be introduced. This course runs for the first five weeks of the quarter.

**PHYSICS 492. Topological Quantum Computation. 2 Units.**

This course will be an introduction to topological quantum computation (TQC), which has recently emerged as an exciting approach to constructing fault-tolerant quantum computers. We start with a review of some basics of quantum computing, 2D topological phases of matter, Abelian/non-Abelian anyons, etc. Then we introduce the concept of TQC and study some examples such as the toric/surface code and Levin-Wen string-net model. We continue to talk about the mathematical theory of anyons including modular tensor categories, braid groups, 6j-symbols, Pentagon Equations. We study the issue of universality for different systems. Lastly, we show the equivalence of TQC with standard circuit model. Additional topics include complexity classes, Jones polynomials, topological field theories, etc. Prerequisite: Basic knowledge of quantum mechanics and condensed matter physics. Some knowledge of category theory and representation theory is useful but is not required. The course will run the first five weeks.

**PHYSICS 50. Astronomy Laboratory and Observational Astronomy. 3 Units.**

Introduction to observational astronomy emphasizing the use of optical telescopes. Observations of stars, nebulae, and galaxies in laboratory sessions with telescopes at the Stanford Student Observatory. Meets at the observatory one evening per week from dusk until well after dark, in addition to day-time lectures each week. No previous physics required. Limited enrollment.

**PHYSICS 59. Frontiers of Physics Research. 1 Unit.**

Recommended for prospective Physics or Engineering Physics majors or anyone with an interest in learning about the big questions and unknowns that physicists tackle in their research at Stanford. Weekly faculty presentations, in some cases followed by tours of experimental laboratories where the research is conducted.

**PHYSICS 61. Mechanics and Special Relativity. 4 Units.**

(First in a three-part advanced freshman physics series: PHYSICS 61, PHYSICS 63, PHYSICS 65.) This course covers Einstein's special theory of relativity and Newtonian mechanics at a level appropriate for students with a strong high school mathematics and physics background, who are contemplating a major in Physics or Engineering Physics, or are interested in a rigorous treatment of physics. Postulates of special relativity, simultaneity, time dilation, length contraction, the Lorentz transformation, causality, and relativistic mechanics. Central forces, contact forces, linear restoring forces. Momentum transport, work, energy, collisions. Angular momentum, torque, moment of inertia in three dimensions. Damped and forced harmonic oscillators. Uses the language of vectors and multivariable calculus. In order to register for this class students must EITHER have already taken an introductory Physics class (20, 40, or 60 sequence) or have taken the Physics Placement Diagnostic at <https://physics.stanford.edu/academics/undergraduate-students/placement-diagnostic>. Recommended prerequisites: Mastery of mechanics at the level of AP Physics C and AP Calculus BC or equivalent. Corequisite: MATH 51 or MATH 61CM or MATH 61DM.

**PHYSICS 62. Mechanics Laboratory. 1 Unit.**

Introduction to laboratory techniques, experiment design, data collection and analysis simulations, and correlating observations with theory. Labs emphasize discovery with open-ended questions and hands-on exploration of concepts developed in PHYSICS 61 including Newton's laws, conservation laws, rotational motion. Pre- or corequisite PHYSICS 61. In this unusual pandemic year we have planned remote lab activity for you. These labs are a mix of online labs as well as hands-on exercises you can do at home, in a dorm or wherever you may be. The class will be structured with an online Zoom section, where you and others in your section will meet with a TA and go over your results, and do some group exercises. You can do the online materials with a virtual lab partner, we encourage you to get the benefit of someone to collaborate on your analysis and observations. We will be sending every enrolled student a kit of hands-on lab materials, you will get more details the first week of class.

**PHYSICS 63. Electricity, Magnetism, and Waves. 4 Units.**

(Second in a three-part advanced freshman physics series: PHYSICS 61, PHYSICS 63, PHYSICS 65.) This course covers the foundations of electricity and magnetism for students with a strong high school mathematics and physics background, who are contemplating a major in Physics or Engineering Physics, or are interested in a rigorous treatment of physics. Electricity, magnetism, and waves with some description of optics. Electrostatics and Gauss' law. Electric potential, electric field, conductors, image charges. Electric currents, DC circuits. Moving charges, magnetic field, Ampere's law. Solenoids, transformers, induction, AC circuits, resonance. Relativistic point of view for moving charges. Displacement current, Maxwell's equations. Electromagnetic waves, dielectrics. Diffraction, interference, refraction, reflection, polarization. Prerequisite: PHYSICS 61 and MATH 51 or MATH 61CM. Pre- or corequisite: MATH 52 or MATH 62CM.

**PHYSICS 64. Electricity, Magnetism and Waves Laboratory. 1 Unit.**

Introduction to multimeters, breadboards, function generators and oscilloscopes. Emphasis on student-developed design of experimental procedure and data analysis for topics covered in PHYSICS 63: electricity, magnetism, circuits, and optics. Pre- or corequisite: PHYSICS 63.

**PHYSICS 65. Quantum and Thermal Physics. 4 Units.**

(Third in a three-part advanced freshman physics series: PHYSICS 61, PHYSICS 63, PHYSICS 65.) This course introduces the foundations of quantum and thermodynamics for students with a strong high school mathematics and physics background, who are contemplating a major in Physics or Engineering Physics, or are interested in a rigorous treatment of physics. Topics related to quantum mechanics include: atoms, electrons, nuclei. Experimental evidence for physics that is not explained by classical mechanics and E&M. Quantization of light, Planck's constant. Photoelectric effect, Compton and Bragg scattering. Bohr model, atomic spectra. Matter waves, wave packets, interference. Fourier analysis and transforms, Heisenberg uncertainty relationships. Particle-in-a-box, simple harmonic oscillator, barrier penetration, tunneling. Topics related to thermodynamics: limitations of classical mechanics in describing systems with a very large number of particles. Ideal gas, equipartition, heat capacity, definition of temperature, entropy. Brief introduction to kinetic theory and statistical mechanics. Maxwell speed distribution, ideal gas in a box. Laws of thermodynamics. Cycles, heat engines, free energy. Prerequisites: PHYSICS 61 & PHYSICS 63.

**PHYSICS 67. Introduction to Laboratory Physics. 1 Unit.**

Methods of experimental design, data collection and analysis, statistics, curve fitting and model validation used in experimental science. Study of common data analysis techniques drawn via example measurements from electronics, optics, heat, and modern physics. Lecture format only for AY2020/2021. Required for PHYSICS 60 series Physics and Engineering Physics majors; recommended for PHYSICS 40 series students who intend to major in Physics or Engineering Physics. Pre- or corequisite: PHYSICS 65 or PHYSICS 43.

**PHYSICS 70. Foundations of Modern Physics. 4 Units.**

Required for Physics or Engineering Physics majors who completed the PHYSICS 40 series. Introduction to special relativity: reference frames, Michelson-Morley experiment. Postulates of relativity, simultaneity, time dilation. Length contraction, the Lorentz transformation, causality. Doppler effect. Relativistic mechanics and mass, energy, momentum relations. Introduction to quantum physics: atoms, electrons, nuclei. Quantization of light, Planck constant. Photoelectric effect, Compton and Bragg scattering. Bohr model, atomic spectra. Matter waves, wave packets, interference. Fourier analysis and transforms, Heisenberg uncertainty relationships. Schrödinger equation, eigenfunctions and eigenvalues. Particle-in-a-box, simple harmonic oscillator, barrier penetration, tunneling, WKB and approximate solutions. Time-dependent and multi-dimensional solution concepts. Coulomb potential and hydrogen atom structure. Prerequisites: PHYSICS 41, PHYSICS 43. Pre or corequisite: PHYSICS 45. Recommended: prior or concurrent registration in MATH 53.

**PHYSICS 801. TGR Project. 0 Units.****PHYSICS 802. TGR Dissertation. 0 Units.****PHYSICS 81N. Science on the Back of the Envelope. 3 Units.**

Understanding the complex world around us quantitatively, using order of magnitude estimates and dimensional analysis. Starting from a handful of fundamental constants of Nature, one can estimate complex quantities such as cosmological length and time scales, size of the atom, height of Mount Everest, speed of tsunami, energy density of fuels and climate effects. Through these examples students learn the art of deductive thinking, fundamental principles of science and the beautiful unity of nature.

**PHYSICS 83N. Physics in the 21st Century. 3 Units.**

Preference to freshmen. This course provides an in-depth examination of frontiers of physics research, including fundamental physics, cosmology, and physics of the future. Questions such as: What is the universe made of? What is the nature of space, time, and matter? What can we learn about the history of the universe and what does it tell us about its future? A large part of 20th century was defined by revolutions in physics & everyday applications of electromagnetism, relativity, and quantum mechanics. What other revolutions can physics bring to human civilization in the 21st century? What is quantum computing? What can physics say about consciousness? What does it take to visit other parts of the solar system, or even other stars? We will also learn to convey these complex topics in engaging and diverse terms to the general public through writing and reading assignments, oral presentations, and multimedia projects. No prior knowledge of physics is necessary; all voices are welcome to contribute to the discussion about these big ideas. Learning Goals: By the end of the quarter you will be able to explain the major questions that drive physics research to your friends and peers. You will understand how scientists study the impossibly small and impossibly large and be able to convey this knowledge in clear and concise terms.

**PHYSICS 91SI. Practical Computing for Scientists. 2 Units.**

Essential computing skills for researchers in the natural sciences. Helping students transition their computing skills from a classroom to a research environment. Topics include the Unix operating system, the Python programming language, and essential tools for data analysis, simulation, and optimization. More advanced topics as time allows. Prerequisite: CS106A or equivalent.

**PHYSICS 93SI. Beyond the Laboratory: Physics, Identity, and Society. 1-2 Unit.**

Beyond its laws and laboratories, what can physics teach us about society and ourselves? How do physicists' identities impact the types of scientific questions that are asked throughout history? And who do we call a physicist? This course seeks to address questions such as these, with an eye to understanding how physics relates to history, politics, and our own identities as young researchers. Students will develop a broader appreciation for where physics comes from, how it relates to themselves, and how they can shape its future. No prior knowledge of physics is necessary; all voices are welcome to contribute to the discussion about these big ideas. As an optional addendum to 93SI, students can participate in POISE (Physics Outreach through Inclusive Science Education), an intensive spring break program in which the themes discussed during the course will be explored in more depth. During POISE, students will develop short workshops for high school students that are geared towards making Physics interesting and accessible. In addition, we will take frequent off-campus trips to Bay Area national labs, museums, companies, the beach, camping sites, and more! Our intention is to create a retreat-style experience in which students can learn more about themselves and each other as Physicists, and put their knowledge to good use in the classroom. Those wishing to participate in the spring break component should apply here, <https://goo.gl/forms/KAOA0aCjD7QxxVbW2>, and expect to be enrolled in 2 units. Those who are interested in only the course component should apply here, <https://goo.gl/forms/xlrsDP0V2ESkMnbS2>, and expect to be enrolled in 1 unit.

**PHYSICS 94SI. Diverse Perspectives in Physics. 1 Unit.**

Have you ever wondered what it is like to be a professor, or what you could do with physics beyond academia? Do you want to hear about the life stories of people with diverse backgrounds who have studied or are studying physics? Professors and industry researchers possessing a diverse set of identities and backgrounds will share their journey in physics and their career trajectories, emphasizing their personal lives and experiences as undergraduates and graduate students. A Q&A session will follow. A free meal will be provided each session!

**PHYSICS 95Q. The Philosophies of Three Great Physicists. 3 Units.**

Richard Feynman has famously said, Philosophy of science is about as useful to scientists as ornithology is to birds. A closer look at key moments in the history of physics, however, reveals a different picture. Contrary to the misconception that philosophy has nothing to offer to science in general, and physics in particular, watershed moments in the development of physics were inspired and motivated by deeply held philosophical principles. Similarly, important developments in physics have generated important and difficult philosophical questions. In this sophomore seminar we will explore three significant moments in the development of physics surrounding the works of Newton, Einstein, and Bohr. We will analyze the relationship between the prevailing philosophical views they espoused and the physics they produced. How did Newton come to the view of absolute and fixed space and time? What led Einstein to reject the notion of a fixed space and time and propose a relativistic, and even dynamic space-time? What is Bohr's influential doctrine of complementary, and why did several generations of physicists believe it to be an adequate philosophical response to quantum mechanics? We will see that the relationship between philosophy and physics is more similar to the relationship between mathematics and physics where progress in one area is often preceded and followed by progress in the second.

**PHYSICS 96N. Harmony and the Universe. 3 Units.**

Harmony is a multifaceted concept that has profoundly connects music, mathematics, physics, philosophy, physiology, and psychology. We will explore the evolution of our understanding of harmony and its immediate application in the function of musical instruments, and employ it as a nexus to understand its role in revolutionary scientific advances in gravity, relativity, quantum mechanics, and cosmology. In these explorations, we will examine some of the fundamental mathematical tools which provide us our current understanding of harmony. We will also see how the some concepts surrounding harmony are in tension, if not conflict, and how some great thinkers have followed them down down blind alleys and dead ends. The aim of the course is to show the enormous consequences of harmony in the evolution of our understanding of the universe, and how science itself progresses in fits, starts, and setbacks as old ideas intermingle with new developments. We will also see how objective/quantitative aspects of harmony interact with subjective/qualitative considerations, and how cultural perspectives and prejudices can affect the progression of science.