PHYSICS

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http://physics.yale.edu
M.S., M.Phil., Ph.D.

Chair
Sarah Demers

Director of Graduate Studies
Helen Caines (helen.caines@yale.edu)

Professors Charles Ahn (*Applied Physics*), Yoram Alhassid, Thomas Appelquist, Charles Bailyn (*Astronomy*), O. Keith Baker, Charles Baltay (*Emeritus*), Sean Barrett, Joerg Bewersdorf (*Cell Biology*), Helen Caines, Hui Cao (*Applied Physics*), Richard Casten (*Emeritus*), Flavio Cavanna (*Adjunct*), Paolo Coppi (*Astronomy*), Sarah Demers, Thierry Emonet (*Molecular, Cellular, and Developmental Biology*), Paul Fleury (*Emeritus*), Marla Geha (*Astronomy*), Steven Girvin, Larry Gladney, Leonid Glazman, Walter Goldberger, Jack Harris, John Harris (*Emeritus*), Karsten Heeger, Victor Henrich (*Emeritus*), Jonathon Howard (*Molecular Biophysics and Biochemistry*), Francesco Iachello (*Emeritus*), Sohrab Ismaill-Beigi (*Applied Physics*), Steve Lamoreaux, Konrad Lehnert, Andre Levchenko (*Biomedical Engineering*), Reina Maruyama, Simon Mochrie, Vincent Moncrief, Daisuke Nagai, Priyamvada Natarajan (*Astronomy*), Andrew Neitzke (*Mathematics*), Corey O'Hern (*Mechanical Engineering and Materials Science*), Vidvus Ozolins (*Applied Physics*), Ornella Palamara (*Adjunct*), Peter Parker (*Emeritus*), Daniel Prober (*Applied Physics*), Nicholas Read, Robert Schoelkopf (*Applied Physics*), John Schotland (*Mathematics*), Jurgen Schukraft (*Adjunct*), Ramamurti Shankar, Witold Skiba, A. Douglas Stone (*Applied Physics*), Hong Tang (*Engineering*), Paul Tipton, Thomas Ullrich (*Adjunct*), C. Megan Urry, Frank van den Bosch (*Astronomy*), Pieter van Dokkum (*Astronomy*), John Wettlaufer (*Earth and Planetary Sciences*), Robert Wheeler (*Emeritus*), Werner Wolf (*Emeritus*), Michael Zeller (*Emeritus*)

Associate Professors Damon Clark (*Molecular, Cellular, and Developmental Biology*), David C. Moore, Michael Murrell (*Biomedical Engineering*), Nir Navon, Laura Newburgh, Nikhil Padmanabhan, David Poland, Peter Rakich (*Applied Physics*), Alison Sweeney

Assistant Professors Charles Brown, Meng Cheng, Eduardo da Silva Neto, Laura Havener, Yu He (*Applied Physics*), Christopher Lynn, Benjamin Machta, Owen Miller (*Applied Physics*), Chiara Mingarelli, Ian Moult, Shruti Puri (*Applied Physics*), Diana Qiu (*Mechanical Engineering and Materials Science*)

Lecturers Mehdi Ghiassi-Nejad, Caitlin Hansen, Stephen Irons, Steven Konezny, Rona Ramos, Adriane Steinacker

FIELDS OF STUDY

Fields include Astrophysics and Cosmology; Atomic, Molecular and Optical Physics; Biological Physics; Condensed Matter; Gravitational Physics; Nuclear Physics; Particle Physics; Quantum Physics; and other areas in collaboration with the School of Engineering & Applied Science and the departments of Applied Physics; Astronomy;

Chemistry; Earth and Planetary Sciences; Molecular Biophysics and Biochemistry; and Molecular, Cellular, and Developmental Biology.

INTEGRATED GRADUATE PROGRAM IN PHYSICAL AND ENGINEERING BIOLOGY (PEB)

Students applying to the Ph.D. program in Physics with a concentration in Biological Physics may also apply to the PEB program. See the description under Non-Degree-Granting Programs, Councils, and Research Institutes for course requirements and https://peb.yale.edu for more information about the benefits of this program and application instructions.

QUANTUM MATERIALS SCIENCE AND ENGINEERING CERTIFICATE (QMSE)

Students applying to the Ph.D. program in Physics with a concentration in quantum materials can apply to the Quantum Materials Science and Engineering (QMSE) certificate program. See the description under Non-Degree-Granting Programs, Councils, and Research Institutes for course requirements and https://qmse.yale.edu for more information about the benefits of the program and application instructions.

SPECIAL REQUIREMENTS FOR THE PH.D. DEGREE

To complete the course requirements, students are expected to take one research course, two seminar courses, and a set of seven credit-hour courses: six foundational courses and one elective.

Six Core Courses

PHYS 5000	Advanced Classical Mechanics	1
PHYS 5020	Electromagnetic Theory I	1
PHYS 5060	Mathematical Methods of Physics	1
PHYS 5080	Quantum Mechanics I	1
PHYS 5100	Quantum Mechanics II	1
PHYS 5120	Statistical Physics I	1

These six courses serve to complete a student's undergraduate core training in classical and quantum physics. For the seventh course, students may select from the list of graduate elective courses offered by the Departments of Physics or Applied Physics. Courses offered by other departments may also qualify as advanced electives, with the approval of the director of graduate studies (DGS).

Students entering the program with a prior master's degree may waive core course requirements. Students without a previous master's can take a core course pass-out exam at the start of the course's term. Those who successfully demonstrate knowledge of the course topics are excused from taking that core course but must replace the credit hours with an approved advanced elective.

In addition to the core courses, all students must engage in a PHYS 9900, Special Investigations, research project by the end of their second year of study. Incoming students are also required to take PHYS 5150, Topics in Modern Physics Research, in the fall, and PHYS 5900, Responsible Conduct in Research for Physical Scientists in the spring.

By the end of a student's third year, they must participate in a two-part qualifying event. Part one is a Research Qualifying Event (RQE) consisting of an oral presentation on research completed during their required PHYS 9900, Special Investigation course. Students will present their research and be evaluated on their presentation by the DGS and their research adviser. Part two is a Written Qualifying Event (WQE) consisting of four written components on classical mechanics, electromagnetic theory, statistical mechanics, and quantum mechanics. Each portion of the WQE should be completed after the student has taken, or passed out of, the relevant courses. Students will receive feedback after each portion of the qualifying event. The RQE and WQE are not graded but rather serve as learning milestones. Students may take the qualifying events in any order.

Before starting their fourth year of study, students must submit their thesis prospectus, as presented to and approved by their core thesis committee. Students who have completed their required course credits with satisfactory grades (two Honors and an overall High Pass average), taken the qualifying events, and submitted an acceptable thesis prospectus are recommended for advancement to candidacy and to receive their M.S. and M.Phil en route. Students entering the program with a master's degree in physics or a related field may waive equivalent graduate-level core courses with approval from the DGS without the requirement of replacing course credits. Students who have waived courses will advance to candidacy but will not receive an M.S. en route from the department.

The teaching experience is regarded as an integral part of the graduate training program. Students are expected to serve four terms as teaching fellows during their studies, usually in the first two years. Students needing additional funding support from the graduate school may be required to teach additional terms. Students who have completed their teaching requirements may also volunteer to teach for additional pay with prior approval from their primary adviser and the DGS.

There is no foreign language requirement in the physics program. However, non-native English speakers who received a score of 25 or below on the TOEFL Speaking section or a 7.5 or below on the IELTS Speaking section are required to participate in a Summer English Language program at Yale in August before matriculation. These students are required to demonstrate English proficiency before they are permitted to teach.

Formal association with a dissertation adviser typically begins after the second year, once the qualifying events have been passed and the required coursework completed. An adviser from a department other than Physics can be chosen in consultation with the DGS, provided the dissertation topic is deemed suitable for a physics Ph.D.

MASTER'S DEGREES

M.Phil. Students who have successfully presented their prospectus and advanced to candidacy qualify for the M.Phil. degree.

M.S. Terminal M.S. degrees are only awarded to students withdrawing from the Ph.D. program after meeting the course requirements but before submitting a thesis prospectus. Requirements for the terminal M.S. are the successful completion of all six core courses listed above, in addition to completing either Special Investigations or an advanced elective (all with a satisfactory record). Students receiving their M.S. en route must have completed all coursework, including PHYS 9900 and an advanced elective. Unless otherwise requested, M.S. en route degrees are awarded once the student has advanced to candidacy.

Additional program information can be found on the Physics website under Academics —Graduate Studies.

COURSES

PHYS 5000a, Advanced Classical Mechanics Jack Harris
Newtonian dynamics, Lagrangian dynamics, and Hamiltonian dynamics. Rigid bodies and Euler equations. Oscillations and eigenvalue equations. Classical chaos. Introduction to dynamics of continuous systems.

PHYS 5020b, Electromagnetic Theory I Staff
Classical electromagnetic theory including boundary-value problems and applications of Maxwell equations. Macroscopic description of electric and magnetic materials. Wave propagation.

PHYS 5060a, Mathematical Methods of Physics Simon Mochrie
Survey of mathematical techniques useful in physics. Includes vector and tensor analysis, group theory, complex analysis (residue calculus, method of steepest descent), differential equations and Green's functions, and selected advanced topics.

PHYS 5080a, Quantum Mechanics I Steve Lamoreaux
The principles of quantum mechanics with application to simple systems. Canonical formalism, solutions of Schrödinger's equation, angular momentum, and spin.

PHYS 5100b, Quantum Mechanics II Staff
Approximation methods, scattering theory, and the role of symmetries. Relativistic wave equations. Second quantized treatment of identical particles. Elementary introduction to quantized fields.

PHYS 5120b, Statistical Physics I Staff
Review of thermodynamics, the fundamental principles of classical and quantum statistical mechanics, canonical and grand canonical ensembles, identical particles, Bose and Fermi statistics, phase transitions and critical phenomena, enormalization group, irreversible processes, fluctuations.

PHYS 5150a, Topics in Modern Physics Research Staff
A comprehensive introduction to the various fields of physics research carried out in the department and a formal introduction to scientific reading, writing, and presenting.

PHYS 5170b / ENAS 5170b / MB&B 5170b / MCDB 5170b, Methods and Logic in Interdisciplinary Research Corey O'Hern and Emma Carley
This full PEB class is intended to introduce students to integrated approaches to research. Each week, the first of two sessions is student-led, while the second session is led by faculty with complementary expertise and discusses papers that use different approaches to the same topic (for example, physical and biological or experiment and theory).

PHYS 5220b, Introduction to Atomic Physics Staff
The course is intended to develop basic theoretical tools needed to understand current research trends in the field of atomic physics. Emphasis is given to laser-spectroscopic methods including laser cooling and trapping. Experimental techniques discussed when appropriate.

PHYS 5380a, Introduction to Relativistic Astrophysics and General Relativity Walter Goldberger
Basic concepts of differential geometry (manifolds, metrics, connections, geodesics, curvature); Einstein's equations and their application to such areas as cosmology, gravitational waves, black holes.

PHYS 5420b, Introduction to Elementary Particle Physics Staff
An overview of particle physics, including an introduction to the standard model, experimental techniques, symmetries, conservation laws, the quark-parton model, and open questions in particle physics.

PHYS 5450Lb, Modern Physics Measurements Staff
A laboratory course with experiments and data analysis in soft and hard condensed matter, nuclear and elementary particle physics.

PHYS 5480a / APHY 5480a, Solid State Physics I Yu He
A two-term sequence (with APHY 549) covering the principles underlying the electrical, thermal, magnetic, and optical properties of solids, including crystal structures, phonons, energy bands, semiconductors, Fermi surfaces, magnetic resonance, phase transitions, and superconductivity.

PHYS 5490b / APHY 5490b / ENAS 851, Solid State Physics II Vidvuds Ozolins
A two-term sequence (with APHY 548) covering the principles underlying the electrical, thermal, magnetic, and optical properties of solids, including crystal structures, phonons, energy bands, semiconductors, Fermi surfaces, magnetic resonance, phase transitions, and superconductivity.

PHYS 5610a / MB&B 5310a / MCDB 5310a, Modeling Biological Systems I Thierry Emonet and Kathryn Miller-Jensen
Biological systems make sophisticated decisions at many levels. This course explores the molecular and computational underpinnings of how these decisions are made, with a focus on modeling static and dynamic processes in example biological systems. This course is aimed at biology students and teaches the analytic and computational methods needed to model genetic networks and protein signaling pathways. Students present and discuss original papers in class. They learn to model using MatLab in a series of in-class hackathons that illustrate the biological examples discussed in the lectures. Biological systems and processes that are modeled include: (1) gene expression, including the kinetics of RNA and protein synthesis and degradation; (2) activators and repressors; (3) the lysogeny/lysis switch of lambda phage; (4) network motifs and how they shape response dynamics; (5) cell signaling, MAP kinase networks and cell fate decisions; and (6) noise in gene expression. Prerequisites: MATH 115 or 116, BIOL 101–104, or with permission of instructors. This course also benefits students who have taken more advanced biology courses (e.g. MCDB 200, MCDB 310, MB&B 300/301).

PHYS 5620b / AMTH 765b / CB&B 5620b / ENAS 5620b / INP 562b / INP 7562b / MB&B 5620b, Modeling Biological Systems II Thierry Emonet, Jing Yan, and Damon Clark

This course covers advanced topics in computational biology. How do cells compute, how do they count and tell time, how do they oscillate and generate spatial patterns? Topics include time-dependent dynamics in regulatory, signal-transduction, and neuronal networks; fluctuations, growth, and form; mechanics of cell shape and motion; spatially heterogeneous processes; diffusion. This year, the course spends roughly half its time on mechanical systems at the cellular and tissue level, and half on models of neurons and neural systems in computational neuroscience. Prerequisite: a 200-level biology course or permission of the instructor.

PHYS 5700b / ASTR 5700b / PHYS 570, High-Energy Astrophysics Paolo Coppi

A survey of current topics in high-energy astrophysics, including accreting black hole and neutron star systems in our galaxy, pulsars, active galactic nuclei and relativistic jets, gamma-ray bursts, and ultra-high-energy cosmic rays. The basic physical processes underlying the observed high-energy phenomena are also covered.

PHYS 5710b / ENAS 5710b / MB&B 5910b / MCDB 5910b, Integrated Workshop Corey O'Hern

This required course for students in the PEB graduate program involves a series of modules, co-taught by faculty, in which students from different academic backgrounds and research skills collaborate on projects at the interface of physics, engineering, and biology. The modules cover a broad range of PEB research areas and skills. The course starts with an introduction to MATLAB, which is used throughout the course for analysis, simulations, and modeling.

PHYS 5900b / APHY 5900b, Responsible Conduct in Research for Physical Scientists Staff

A review and discussion of best practices of conduct in research including scientific integrity and misconduct; mentorship; data management; and diversity, equity, and inclusion in science.

PHYS 6000b / ASTR 6000b, Cosmology Nikhil Padmanabhan

A comprehensive introduction to cosmology at the graduate level. The standard paradigm for the formation, growth, and evolution of structure in the universe is covered in detail. Topics include the inflationary origin of density fluctuations; the thermodynamics of the early universe; assembly of structure at late times and current status of observations. The basics of general relativity required to understand essential topics in cosmology are covered. Advanced undergraduates may register for the course with permission of the instructor.

PHYS 6010a / APHY 6600a, Quantum Information and Computation Shruti Puri

This course focuses on the theory of quantum information and computation. We cover the following tentative list of topics: overview of postulates of quantum mechanics and measurements, quantum circuits, physical implementation of quantum operations, introduction to computational complexity, quantum algorithms (DJ, Shor's, Grover's, and others as time permits), decoherence and noisy quantum channels, quantum error-correction and fault-tolerance, stabilizer formalism, error-correcting codes (Shor, Steane, surface-code, and others as time permits), quantum key distribution, quantum Shannon theory, entropy, and data compression.

PHYS 6100a / APHY 6100a, Quantum Many-Body Theory Yoram Alhassid
Identical particles and second quantization. Electron tunneling and spectral function. General linear response theory. Approximate methods of quantum many-body theory. Dielectric response, screening of long-range interactions, electric conductance, collective modes, and photon absorption spectra. Fermi liquid; Cooper and Stoner instabilities; notions of superconductivity and magnetism. BCS theory, Josephson effect, and Majorana fermions in condensed matter; superconducting qubits. Bose-Einstein condensation; Bogoliubov quasiparticles and solitons.

PHYS 6120a / APHY 6280a, Statistical Physics II Nicholas Read
An advanced course in statistical mechanics. Topics may include mean field theory of and fluctuations at continuous phase transitions; critical phenomena, scaling, and introduction to the renormalization group ideas; topological phase transitions; dynamic correlation functions and linear response theory; quantum phase transitions; superfluid and superconducting phase transitions; cooperative phenomena in low-dimensional systems.

PHYS 6200a, Relativistic Field Theory I Thomas Appelquist
The fundamental principles of quantum field theory. Interacting theories and the Feynman graph expansion. Quantum electrodynamics including lowest order processes, one-loop corrections, and the elements of renormalization theory.

PHYS 6300b, Relativistic Field Theory II Staff
An introduction to non-Abelian gauge field theories, spontaneous symmetry breakdown, and unified theories of weak and electromagnetic interactions. Renormalization group methods, quantum chromodynamics, and nonperturbative approaches to quantum field theory.

PHYS 6330b / APHY 6330b, Introduction to Superconductivity Yu He
The fundamentals of superconductivity, including both theoretical understandings of basic mechanism and description of major applications. Topics include historical overview, Ginzburg-Landau (mean field) theory, critical currents and fields of type II superconductors, BCS theory, Josephson junctions and microelectronic and quantum-bit devices, and high-Tc oxide superconductors.

PHYS 6750a / APHY 6750a, Principles of Optics with Applications Hui Cao
Introduction to the principles of optics and electromagnetic wave phenomena with applications to microscopy, optical fibers, laser spectroscopy, nanophotonics, plasmonics, and metamaterials. Topics include propagation of light, reflection and refraction, guiding light, polarization, interference, diffraction, scattering, Fourier optics, and optical coherence.

PHYS 6760a / APHY 6760a, Introduction to Light-Matter Interactions Peter Rakich
Optical properties of materials and a variety of coherent light-matter interactions are explored through the classical and quantum treatments. The role of electronic, phononic, and plasmonic interactions in shaping the optical properties of materials is examined using generalized quantum and classical coupled-mode theories. The dynamic response of media to strain, magnetic, and electric fields is also treated. Modern topics are explored, including optical forces, photonic crystals, and metamaterials; multi-photon absorption; and parametric processes resulting from electronic, optomechanical, and Raman interactions.

PHYS 6780b, Computing for Scientific Research Staff
This hands-on lab course introduces students to essential computational and data analysis methods, tools, and techniques and their applications to solve problems in physics. The course introduces some of the most important and useful skills, concepts, methods, tools, and relevant knowledge to get started in scientific research broadly defined, including theoretical, computational, and experimental research. Students learn basic programming in Python, data analysis, statistical tools, modeling, simulations, machine learning, high-performance computing, and their applications to problems in physics and beyond.

PHYS 6790b / APHY 6790b, Nonlinear Optics and Lasers Logan Wright
Properties and origins of the nonlinear susceptibility; Sum-freq, diff-freq and 2nd-harmonic generation; Intensity-dependent refractive index; Optical phase conjugation; Self-focusing, self-phase modulation, solitons; Stimulated light scattering; Fixed points, bifurcations; Amplification; Rate equations; Relaxation oscillations, frequency pulling; Hole burning; Q-switching; Semiconductor and DFB lasers; Mode-locking; Injection-locking; Intense-field NLO and QM laser theory (time permitting)

PHYS 7460a / ASTR 7460a / MATH 7460a, Global Properties of Nonlinear Relativistic Fields Vincent Moncrief
Many relativistic field equations of interest in mathematical physics, astrophysics and cosmology are intrinsically nonlinear. Notable examples are various nonlinear wave equations, the Maxwell-Klein-Gordon equations, the Yang-Mills-Higgs equations and the Einstein field equations of general relativity. Techniques for analyzing their global solutions on various manifolds include (higher order) energy estimates and so-called light-cone estimates. An interesting question for the Einstein equations is whether the so-called "cosmological principle," according to which only the very special manifolds admitting (spatially) homogeneous and isotropic metrics need be considered for cosmology, is firmly established or whether this principle can be relaxed to allow for much more general manifolds and still be consistent with observations. Another issue is how the Thurston geometrization theorem, established by Hamilton and Perlman via Ricci flow, relates to the "cosmic censorship conjecture" of Roger Penrose, often regarded as the main open mathematical problem of general relativity.

PHYS 9900a or b, Special Investigations Staff
Directed research by arrangement with individual faculty members and approved by the DGS in a student's second year. Students are expected to propose and complete a term-long research project. The culmination of the project is a presentation that fulfills the departmental requirement for the research qualifying event.