**PHYSICS**

**Director of undergraduate studies:** Simon Mochrie, 68C SPL, 436-4809, dus.physics@yale.edu; physics.yale.edu/academics/undergraduate-studies

Physics forms a foundation for all other sciences. The various undergraduate courses and degree programs offered by the Physics department provide students with a thorough preparation in physics for any career, as well as the general background in physics that should be part of a liberal education. The department offers four different introductory sequences and two degree programs. Also offered are introductory courses that fulfill the science and quantitative reasoning distributional requirements and are appropriate for non-science majors. Combined majors are available in Mathematics and Physics (http://catalog.yale.edu/ycps/subjects-of-instruction/mathematics-physics), Astronomy (http://catalog.yale.edu/ycps/subjects-of-instruction/astronomy), Physics and Philosophy (http://catalog.yale.edu/ycps/subjects-of-instruction/physics-philosophy), and Physics and Geosciences (http://catalog.yale.edu/ycps/subjects-of-instruction/physics-geosciences). Applied Physics (http://catalog.yale.edu/ycps/subjects-of-instruction/applied-physics) is a closely related major.

Two different majors are offered in Physics: the B.S. and the B.S. with an intensive major. Students in either program acquire advanced training in physics, mathematics, and related topics through the core courses. They use electives to design individualized programs with more depth or breadth, depending on their needs and interests. Both degree programs require research experience through PHYS 471 and 472—one term for the B.S. degree and two terms for the B.S. degree with an intensive major. Both programs are excellent preparation for a wide variety of professional school in business, law, or medicine; graduate school in engineering or other sciences; or careers in business, consulting, financial services, government service, or teaching.

The B.S. program with an intensive major is distinguished by depth of study in advanced physics courses and prepares students to study physics or closely related physical sciences in graduate school. The director of undergraduate studies can help students in the B.S. program prepare for graduate school in physics by recommending appropriate electives to supplement the core courses.

**COURSES FOR NONMAJORS AND MAJORS**

A guide to selecting physics courses (http://physics.yale.edu/academics/undergraduate-studies/guide-introductory-physics-course) is available to aid in course selection. Questions about placement should be addressed to the DUS.

**Introductory courses with no calculus requirement** Physics courses numbered 120 or below are for students with little or no previous experience in physics who do not plan to major in the natural sciences. These courses have no college-level mathematics requirement and do not satisfy the medical school requirement.

**Introductory calculus-based lecture sequences**

1. PHYS 170, 171 is aimed at students who will probably not major in the physical sciences but who may be interested in medical and biological sciences. Knowledge of differential and integral calculus at the level of MATH 112 or equivalent is a prerequisite. MATH 115 should be taken concurrently with PHYS 171.

2. PHYS 180, 181 is aimed at students who plan to major in the physical sciences. Calculus at the level of MATH 112 is a prerequisite; MATH 115 and 120 should be taken concurrently.

3. PHYS 200, 201 is for students with a strong background in mathematics and physics who plan to major in the physical sciences. Calculus at the level of MATH 115 is presumed. MATH 120 and either MATH 222 or 225 should be taken previously or concurrently.

4. PHYS 260, 261 is intended for students who have had excellent prior training in mathematical methods and quantitative analysis; a solid foundation in physics is required. One of MATH 120, ENAS 151, PHYS 301, or MATH 230, 231 or equivalent should be taken concurrently with PHYS 260, 261.

**Introductory laboratories** Two different introductory laboratory sequences are offered: PHYS 165L, 166L, and PHYS 205L, 206L. Each of these laboratory courses earns one-half course credit. Students normally take the laboratory courses associated with the introductory physics sequence in which they are enrolled.

1. PHYS 165L, 166L is an introductory laboratory sequence aimed at students interested in the biological sciences and medicine. Related lecture courses are PHYS 170, 171, and PHYS 180, 181.

2. PHYS 205L, 206L is for students who plan to major in the physical sciences. Related lecture courses are PHYS 180, 181; PHYS 200, 201; and PHYS 260, 261. Students who take the lecture courses in their first year are advised to start this laboratory sequence with PHYS 205L in the spring of their first year or in the fall of sophomore year.

**Advanced electives** A series of 340-level electives explores special topics of interest to both majors and nonmajors. The electives are open to any student in Yale College who has completed a year of introductory calculus-based physics (PHYS 170, 171; or 180, 181; or 200, 201; or 260, 261). The offerings for 2017–2018 include PHYS 341 and PHYS 343.

**PREREQUISITES**

**B.S. degree program** The prerequisites are an introductory lecture course sequence with a mathematics sequence equivalent to, or more advanced than, the corequisite of the physics options. The following options are appropriate: PHYS 170, 171 with MATH 112, 115;
A program for a student completing the Physics B.S. in three years might be:

...as illustrated below...

...to allow the greatest amount of flexibility in course selection. It is possible, however, to complete either program in a total of six...

For both the standard B.S. degree and the B.S. degree with an intensive major, students are advised to begin the program in their first...

...undeclared sophomores who are interested in Physics or related majors are encouraged to meet with the DUS to discuss their questions...

...first-year students and undeclared sophomores who are interested in Physics or related majors are encouraged to meet with the DUS to discuss their questions and proposed programs.

For both the standard B.S. degree and the B.S. degree with an intensive major, students are advised to begin the program in their first year to allow the greatest amount of flexibility in course selection. It is possible, however, to complete either program in a total of six terms, as illustrated below.

A program for a student completing the Physics B.S. in three years might be:

<table>
<thead>
<tr>
<th>First-Year or Sophomore</th>
<th>Sophomore or Junior</th>
<th>Senior</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHYS 170, 171, or 180, 181, or 200, 201, or 260, 261</td>
<td>PHYS 206L</td>
<td>APHY 439 or PHYS 440</td>
</tr>
<tr>
<td>PHYS 205L</td>
<td>PHYS 301</td>
<td>PHYS 471 or 472</td>
</tr>
<tr>
<td>Mathematics corequisites</td>
<td>PHYS 401</td>
<td>Two advanced electives</td>
</tr>
<tr>
<td></td>
<td>PHYS 402</td>
<td></td>
</tr>
<tr>
<td></td>
<td>One advanced elective</td>
<td></td>
</tr>
</tbody>
</table>
A program for a student completing the intensive major in three years might be:

First-Year or Sophomore
- PHYS 170, 171, or 180, 181, or 200, 201, or 260, 261
- PHYS 205L
Mathematics corequisites
- PHYS 301

Sophomore or Junior
- PHYS 206L
- PHYS 441

Senior
- PHYS 440

REQUIREMENTS OF THE MAJOR

B.S. DEGREE

Prerequisites
- PHYS 170, 171 or 180, 181 or 200, 201 or 260, 261, with appropriate math coreqs; PHYS 205L, 206L or PHYS 165L, 166L

Number of courses
- 8 term courses beyond prereqs (incl senior req)

Specific courses required
- PHYS 301 or other advanced math course; PHYS 401, 402, and either APHY 439 or PHYS 440, in sequence

Distribution of courses
- 3 advanced electives approved by DUS

Senior requirement
- PHYS 471 or 472 or equivalent

B.S. DEGREE, INTENSIVE MAJOR

Prerequisites
- PHYS 170, 171 or 180, 181 or 200, 201 or 260, 261, with appropriate math coreqs; PHYS 205L, 206L or PHYS 165L, 166L

Number of courses
- 10 term courses beyond prereqs (incl senior req)

Specific courses required
- PHYS 301 or other advanced math course; PHYS 410, 440, 441, 420, 430, in sequence; PHYS 382L

Distribution of courses
- 1 advanced elective approved by DUS

Senior requirement
- PHYS 471 and 472 or equivalent

FACULTY OF THE DEPARTMENT OF PHYSICS

Professors
- †Charles Ahn, Yoram Alhassid, Thomas Appelquist, †Charles Bailyn, O. Keith Baker, Charles Baltay, Sean Barrett, †Hui Cao, Richard Casten (Emeritus), †Paolo Coppi, David DeMille, †Michel Devoret, Bonnie Fleming, †Marla Geha, Steven Girvin, Leonid Glazman, John Harris, Karsten Heeger, †Victor Henrich, †Jonathon Howard, Francesco Iachello, †Sohrab Ismail-Beigi, Steven Lamoreaux, Simon Mochrie, Vincent Moncrief, †Priyamvada Natarajan, Peter Parker (Emeritus), †Daniel Prober, Nicholas Read, Jack Sandweiss (Emeritus), †Robert Schoelkopf, Ramamurti Shankar, Witold Skiba, †A. Douglas Stone, Paul Tipton (Chair), C. Megan Urry, †Pieter van Dokkum, †John Wettlaufer, Michael Zeller (Emeritus)

Associate Professors
- Helen Caines, Sarah Demers, †Thierry Emonet, Walter Goldberger, Jack Harris, Reina Maruyama, Daisuke Nagai, †Corey O’Hern, Nikhil Padmanabhan, David Poland

Assistant Professors
- †Murat Acar, †Eric Michael Brown, Meng Cheng, †Damon Clark, †Liang Jiang, David Moore, †John Murray, Nir Navon, Laura Newburgh, †Peter Rakich

Senior Lecturer
- Sidney Cahn

Lecturers
- Stephen Irons, Rona Ramos, Adriane Steinacker

Helmsley Postdoctoral Associates
- Claudia De Grandi, Savan Kharel

† A joint appointment with primary affiliation in another department.

Courses

* PHYS 050a / APHY 050a, Science of Modern Technology and Public Policy  Daniel Prober
Examination of the science behind selected advances in modern technology and implications for public policy, with focus on the scientific and contextual basis of each advance. Topics are developed by the participants with the instructor and with guest lecturers, and may include nanotechnology, quantum computation and cryptography, renewable energy technologies, optical systems for communication and medical diagnostics, transistors, satellite imaging and global positioning systems, large-scale immunization, and DNA made to order. Enrollment limited to freshmen. Preregistration required; see under Freshman Seminar Program.  SC  RP

* PHYS 100b / APHY 100b / ENAS 100b / EVST 100b / G&G 105b, Energy Technology and Society  Daniel Prober
The technology and use of energy. Impacts on the environment, climate, security, and economy. Application of scientific reasoning and quantitative analysis. Intended for non–science majors with strong backgrounds in math and science. Enrollment limited to 24. For application instructions, visit the course site on Canvas @ Yale.  QR, SC

* PHYS 107b / MB&B 107b, Being Human in STEM  Andrew Miranker and Lynne Regan
A collaboratively-designed, project-oriented course that seeks to examine, understand, and disseminate how diversity of gender, race, religion, sexuality, economic circumstances, etc. shape the STEM experience at Yale and nationally, and that seeks to formulate and implement solutions to issues that are identified. Study of relevant peer-reviewed literature and popular-press articles. Implementation
of a questionnaire and interviews of STEM participants at Yale. Creation of role-play scenarios for provoking discussions and raising awareness. Design and implementation of group interventions.  

* PHYS 115a / HUMS 455a / THST 115, The Physics of Dance  
Sarah Demers Konezny and Emily Coates  
Critical investigation of introductory concepts in physics through the lens of dance. Topics in physics include the normal force, friction, Newton’s laws, projectile motion, potential and kinetic energy, and conservation of energy. Topics in dance include aspects of dance history, contemporary artists who engage with science, and the development of movement studies. Class meetings include movement exercises. Prerequisite: basic trigonometry and algebra. Prior dance experience is not required.  

* PHYS 120b, Quantum Physics and Beyond  
John Harris  
Current topics in modern physics, beginning with quantum physics and continuing through subatomic physics, special and general relativity, cosmology, astrophysics, and string theory.  

PHYS 151a or b / APHY 151a or b / ENAS 151a or b, Multivariable Calculus for Engineers  
Staff  
An introduction to multivariable calculus focusing on applications to engineering problems. Topics include vector-valued functions, vector analysis, partial differentiation, multiple integrals, vector calculus, and the theorems of Green, Stokes, and Gauss. Prerequisite: MATH 115 or equivalent.  

PHYS 165La, General Physics Laboratory  
Staff  
A variety of individually self-contained experiments are roughly coordinated with the lectures in PHYS 170, 171, and 180, 181 and illustrate and develop physical principles covered in those lectures.  

PHYS 166Lb, General Physics Laboratory  
Oliver Baker and Sean Barrett  
A variety of individually self-contained experiments are roughly coordinated with the lectures in PHYS 170, 171, and 180, 181 and illustrate and develop physical principles covered in those lectures.  

* PHYS 170a and PHYS 171b, University Physics for the Life Sciences  
Staff  
An introduction to classical physics with special emphasis on applications drawn from the life sciences and medicine. Fall-term topics include vectors and kinematics, Newton’s laws, momentum, energy, random walks, diffusion, fluid mechanics, mathematical modeling, and statistical mechanics. Spring-term topics include oscillations, waves, sound, electrostatics, circuits, Maxwell’s equations, electromagnetic waves and optics, gene circuits, and quantum mechanics. Essential mathematics are introduced and explained as needed. Completion of MATH 112 or equivalent is prerequisite for PHYS 170. Completion of PHYS 170 is a prerequisite for PHYS 171. MATH 115 is recommended prior to or concurrently with PHYS 171.  

PHYS 180a and PHYS 181b, University Physics  
Adriane Steinacker  
A broad introduction to classical and modern physics for students who have some previous preparation in physics and mathematics. Fall-term topics include Newtonian mechanics, gravitation, waves, and thermodynamics. Spring-term topics include electromagnetism, optics, special relativity, and quantum physics. Concurrently with MATH 115 and 120 or equivalents. See comparison of introductory sequences and laboratories in the YCPS. May not be taken for credit after PHYS 170, 171.  

PHYS 200a and PHYS 201b, Fundamentals of Physics  
Staff  
A thorough introduction to the principles and methods of physics for students who have good preparation in physics and mathematics. Emphasis on problem solving and quantitative reasoning. Fall-term topics include Newtonian mechanics, special relativity, gravitation, thermodynamics, and waves. Spring-term topics include electromagnetism, geometrical and physical optics, and elements of quantum mechanics. Prerequisite: MATH 115 or equivalent. See comparison of introductory sequences and laboratories in the YCPS.  

PHYS 205La or b, Modern Physical Measurement  
Staff  
A two-term sequence of experiments in classical and modern physics for students who plan to major in Physics. In the first term, the basic principles of mechanics, electricity, and magnetism are illustrated in experiments designed to make use of computer data handling and teach error analysis. In the second term, students plan and carry out experiments illustrating aspects of wave and quantum phenomena and of atomic, solid state, and nuclear physics using modern instrumentation. May be begun in either term.  

PHYS 206La or b, Modern Physical Measurement  
Staff  
A two-term sequence of experiments in classical and modern physics for students who plan to major in Physics. In the first term, the basic principles of mechanics, electricity, and magnetism are illustrated in experiments designed to make use of computer data handling and teach error analysis. In the second term, students plan and carry out experiments illustrating aspects of wave and quantum phenomena and of atomic, solid state, and nuclear physics using modern instrumentation.  

* PHYS 260a and PHYS 261b, Intensive Introductory Physics  
Charles Baltay  
The major branches of physics—classical and relativistic dynamics, gravitation, electromagnetism, heat and thermodynamics, statistical mechanics, quantum physics—at a sophisticated level. For students majoring in the physical sciences, Mathematics, and Philosophy who have excellent training in and a flair for mathematical methods and quantitative analysis. Concurrently with MATH 230 and 231, or PHYS 301, or equivalent.  

PHYS 255a / ASTR 255a, Research Methods in Astrophysics  
Marla Geha  
The acquisition and analysis of astrophysical data, including the design and use of ground- and space-based telescopes, computational manipulation of digitized images and spectra, and confrontation of data with theoretical models. Examples taken from current research
at Yale and elsewhere. Use of the Python programming language. A background in high school calculus and physics. No previous programming experience required. QR, SC  RP

**PHYS 301a, Introduction to Mathematical Methods of Physics**  Oliver Baker
Topics include multivariable calculus, linear algebra, complex variables, vector calculus, and differential equations. Designed to give accelerated access to 400-level courses by providing, in one term, the essential background in mathematical methods. Recommended to be taken concurrently with PHYS 401 or 410. Prerequisite: PHYS 170, 171, or 180, 181, or 200, 201, or 260, 261, or permission of instructor. QR

**PHYS 341b, Biological Physics**  Simon Mochrie
An introduction to the physics of biological structures and life processes, and to the burgeoning field of biological physics. Related concepts from probability theory and statistical physics are developed as needed. Prerequisite: PHYS 170, 171, or 180, 181, or 200, 201, or 260, 261, or permission of instructor. Recommended preparation: PHYS 301 or other advanced mathematics course. QR, SC

**PHYS 342a / G&S 342a, Introduction to Earth and Environmental Physics**  John Wettlaufer
A broad introduction to the processes that affect the past, present, and future features of the Earth. Examples include climate and climate change and anthropogenic activities underlying them, planetary history, and their relation to our understanding of Earth’s present dynamics and thermodynamics. Prerequisite: PHYS 170, 171, or 180, 181, or 200, 201, or 260, 261, or permission of instructor. Recommended preparation: familiarity with basic calculus and differential equations. QR, SC

**PHYS 343b / ASTR 343b, Gravity, Astrophysics, and Cosmology**  Laura Newburgh
Introduction to frontier areas of research in astrophysics and cosmology exploring ideas and methods. In—depth discussion of the physics underlying several recent discoveries including extrasolar planets—their discovery, properties, and issues of habitability; black holes—prediction of their properties from GR, observational signatures, and detection; and the accelerating universe—introduction to cosmological models and the discovery of dark energy. Prerequisites: PHYS 170, 171, or 180, 181, or 200, 201, or 260, 261, or permission of instructor. QR, SC

* **PHYS 356b / ASTR 356b, Astrostatistics and Data Mining**  Hector Arce
Introduction to the statistical tools used to analyze and interpret astrophysical data, including common data mining techniques for finding patterns in large data sets and data-based prediction methods. Use of publicly available high-quality astronomical data from large surveys such as SDSS and 2MASS, and from space-based observatories such as Spitzer, Herschel, and WISE. Coding with the Python programming language. Prerequisite: ASTR 255 or equivalent. QR, SC

* **PHYS 382bL, Advanced Physics Laboratory**  Reina Maruyama, Sidney Cahn, Steve Lamoreaux, and Nir Navon
Laboratory experiments with some discussion of theory and techniques. An advanced course focusing on modern experimental methods and concepts in atomic, optical, nuclear, and condensed matter physics. Intended to prepare students for independent research. For majors in the physical sciences. After or concurrently with PHYS 439 or 440, or with permission of instructor. PHYS 206L WR, SC

**PHYS 401a and PHYS 402b, Advanced Classical Physics from Newton to Einstein**  Staff
Advanced physics as the field developed from the time of Newton to the age of Einstein. Topics include mechanics, electricity and magnetism, statistical physics, and thermodynamics. The development of classical physics into a "mature" scientific discipline, an idea that was subsequently shaken to the core by the revolutionary discoveries of quantum physics and relativity. Prerequisite: PHYS 170, 171, or 180, 181, or 200, 201, or 260, 261. Concurrently with PHYS 301 or other advanced mathematics course. QR, SC

**PHYS 410a, Classical Mechanics**  Jack Harris
An advanced treatment of mechanics, with a focus on the methods of Lagrange and Hamilton. Lectures and problems address the mechanics of particles, systems of particles, and rigid bodies, as well as free and forced oscillations. Introduction to chaos and special relativity. Prerequisite: PHYS 170, 171, or 180, 181, or 200, 201, or 260, 261. Concurrently with PHYS 301 or other advanced mathematics course. QR, SC

* **PHYS 420a / APHY 420a, Thermodynamics and Statistical Mechanics**  Nir Navon
An introduction to the laws of thermodynamics and their theoretical explanation by statistical mechanics. Applications to gases, solids, phase equilibrium, chemical equilibrium, and boson and fermion systems. PHYS 301 and 410 or equivalents QR, SC

**PHYS 428a / AMTH 428a / E&EB 428a / G&S 428a, Science of Complex Systems**  Jun Korenaga
Introduction to the quantitative analysis of systems with many degrees of freedom. Fundamental components in the science of complex systems, including how to simulate complex systems, how to analyze model behaviors, and how to validate models using observations. Topics include cellular automata, bifurcation theory, deterministic chaos, self-organized criticality, renormalization, and inverse theory. Prerequisite: PHYS 301, MATH 247, or equivalent. QR, SC

**PHYS 430b, Electromagnetic Fields and Optics**  David Poland
Electrostatics, magnetic fields of steady currents, electromagnetic waves, and relativistic dynamics. Provides a working knowledge of electrodynamics. Prerequisites: PHYS 301 and 410 or equivalents. QR, SC

**PHYS 439a / APHY 439a, Basic Quantum Mechanics**  Peter Rakich
The basic concepts and techniques of quantum mechanics essential for solid-state physics and quantum electronics. Topics include the Schrödinger treatment of the harmonic oscillator, atoms and molecules and tunneling, matrix methods, and perturbation theory. Prerequisites: PHYS 181 or 201, PHYS 301, or equivalents, or permission of instructor. QR, SC
PHYS 440b, Quantum Mechanics and Natural Phenomena I  Witold Skiba
The first term of a two-term sequence covering principles of quantum mechanics with examples of applications to atomic physics. The solution of bound-state eigenvalue problems, free scattering states, barrier penetration, the hydrogen-atom problem, perturbation theory, transition amplitudes, scattering, and approximation techniques. Prerequisite: PHYS 410 or 401. QR, SC

PHYS 441a, Quantum Mechanics and Natural Phenomena II  Witold Skiba
Continuation of PHYS 440. Prerequisite: PHYS 440. QR, SC

PHYS 448a / APHY 448a, Solid State Physics I  Victor Henrich
The first term of a two-term sequence covering the principles underlying the electrical, thermal, magnetic, and optical properties of solids, including crystal structure, phonons, energy bands, semiconductors, Fermi surfaces, magnetic resonances, phase transitions, dielectrics, magnetic materials, and superconductors. Prerequisites: APHY 322, 439, PHYS 420. QR, SC

PHYS 449b / APHY 449b, Solid State Physics II  Vidvuds Ozolins
The second term of the sequence described under APHY 448. QR, SC

PHYS 458a / APHY 458a, 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, and nanostructure physics. Topics include propagation of light, reflection and refraction, guiding light, polarization, interference, diffraction, scattering, Fourier optics, and optical coherence. Prerequisite: PHYS 430. QR, SC

PHYS 460a, Mathematical Methods of Physics  Nicholas Read
Survey of mathematical techniques useful in physics. Physical examples illustrate vector and tensor analysis, group theory, complex analysis (residue calculus, method of steepest descent), differential equations and Green’s functions, and selected advanced topics. Prerequisite: PHYS 301 or other advanced mathematics course. QR

* PHYS 471a and PHYS 472b, Independent Projects in Physics  John Harris
Each student works on an independent project under the supervision of a member of the faculty or research staff. Students participate in a series of seminar meetings in which they present a talk on their project or research related to it. A written report is also submitted. For students with a strong background in Physics course work. RP