PHYSICS

Director of undergraduate studies: John Harris, 311 WL-W, 432-3601, dus.physics@yale.edu; physics.yale.edu/undergraduate-studies

FACULTY OF THE DEPARTMENT OF PHYSICS

Professors  †Charles Ahn, Yoram Alhassid, Thomas Appelquist, †Charles Bailyn, O. Keith Baker, Charles Baltay, Sean Barrett, Cornelius Beausang (Adjunct), †Hui Cao, †Richard Chang (Emeritus), †Paolo Coppi, David DeMille, †Michel Devoret, Bonnie Fleming, †Paul Fleury, Moshe Gai (Adjunct), †Marla Geha, Steven Girvin, Leonid Glazman, John Harris, Karsten Heeger, †Victor Henrich, Jay Hirshfield (Adjunct), †Jonathan Howard, Francesco Iachello, 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), †John Tully, Thomas Ullrich (Adjunct), C. Megan Urry, †Pieter van Dokkum, †John Wettlaufer, Michael Zeller (Emeritus)

Associate Professors  Helen Caines, Sarah Demers, †Eric Dufresne, †Thierry Emonet, Walter Goldberger, Jack Harris, †Sohrab Ismail-Beigi, Daisuke Nagai, †Corey O’Hern, Nikhil Padmanabhan, †A. Elizabeth Rhoades, †Hongxing Tang

Assistant Professors  †Murat Acar, †Damon Clark, †Liang Jiang, Reina Maruyama, David Poland, †Peter Rakich

Senior Lecturer  Sidney Cahn

Lecturers  Stephen Irons, Rona Ramos, †Frank Robinson

† A joint appointment with primary affiliation in another department.

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/archive/2015-2016/ycps/subjects-of-instruction/mathematics-physics), Astrophysics (http://catalog.yale.edu/archive/2015-2016/ycps/subjects-of-instruction/astrophysics), Physics and Philosophy (http://catalog.yale.edu/archive/2015-2016/ycps/subjects-of-instruction/physics-philosophy), and Physics and Geosciences (http://catalog.yale.edu/archive/2015-2016/ycps/subjects-of-instruction/physics-geosciences). Applied Physics (http://catalog.yale.edu/archive/2015-2016/ycps/subjects-of-instruction/applied-physics) is a closely related major.

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 for students with little background in physics and mathematics who will probably not major in the physical sciences but who may be interested in the medical and biological sciences. There is no mathematics prerequisite other than high school mathematics, but MATH 112 and 115 should be taken concurrently.

2. PHYS 180, 181 is for students with some previous background in physics and mathematics 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 are typically taken concurrently.

4. PHYS 260, 261 is intended for students who have had excellent training in and have a flair for 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.

If students have the appropriate mathematics background, they are advised to take a calculus-based physics course. Sir Isaac Newton developed calculus while trying to describe the world around him; it is the natural language of physics. Students enrolled in one of the calculus-based introductory courses will be invited to a series of Chairman’s Teas, which provide an opportunity to discuss topics on the frontiers of physics with faculty and peers. Completion of a calculus-based course also prepares students for the 340-level series of advanced physics electives, which cover special topics of interest to both majors and nonmajors.

A guide to selecting physics courses (http://physics.yale.edu/academics/undergraduate-studies/guide-introductory-physics-course) is available to aid in course selection. PHYS 170, 180, 200, and 260 meet at the same time so that students are easily able to change levels if necessary. Questions about placement should be addressed to the director of undergraduate studies.

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
Many students choose to take more than ten advanced courses. Requirements must be approved by the director of undergraduate studies. In order to pursue their individual interests in sufficient depth, students may also find suitable advanced courses in other departments in the sciences, engineering, and mathematics. Courses taken to satisfy these requirements must be approved by the director of undergraduate studies. In the spring of freshman year or in the fall of sophomore year.

**Advanced electives** A series of 340-level electives explore 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 2015–2016 include PHYS 342, Introduction to Earth and Environmental Physics; PHYS 343, Gravity, Astrophysics, and Cosmology; and PHYS 344, Quantum and Nanoscale Physics.

**Major degree programs** 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 postgraduate activities, including 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.

**Credit/D/Fail courses** Courses taken Credit/D/Fail may not be counted toward the requirements of either major.

**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 sequence. The following options are appropriate: PHYS 170, 171 with MATH 112, 115; or PHYS 180, 181 with MATH 115, 120; or PHYS 200, 201 with MATH 120 and either 225 or 222; or PHYS 260, 261 with MATH 120, ENAS 151, PHYS 301, or MATH 230, 231 or equivalent. In addition, the laboratory sequence PHYS 205L, 206L or PHYS 165L, 166L is required. Students who take these physics and mathematics courses starting in their freshman year may satisfy the prerequisites by the middle of their sophomore year. Students who begin taking physics courses in their sophomore year may also complete either the standard or the intensive major. Students are advised to take mathematics courses throughout their freshman year at the appropriate level.

Eight courses are required beyond the prerequisites, including the senior project. Students must take a mathematics course at the level of, or more advanced than, PHYS 301. Three courses at the core of the major involve advanced study of fundamental topics common to all branches of physics, and must be taken in order. The first two, PHYS 401 and 402, pertain to advanced classical physics (mechanics, statistical physics and thermodynamics, and electromagnetism), and the third, APHY 439 or PHYS 440, covers quantum mechanics. Three advanced elective courses are also required. Suitable advanced courses include the PHYS 340-level electives, an advanced laboratory such as PHYS 382L, and 400-level courses in Physics. Students may also find suitable advanced courses in other departments in the sciences, engineering, and mathematics. Courses taken to satisfy these requirements must be approved by the director of undergraduate studies. In order to pursue their individual interests in sufficient depth, many students choose to take more than the required number of advanced courses.

**Senior requirement for the B.S. degree program** The senior requirement for the standard B.S. degree is fulfilled by receiving a passing grade on a one-term research project in PHYS 471 or 472 or equivalent. Students should consult the director of undergraduate studies for further information.

**B.S. degree program, intensive major** The prerequisites for the B.S. degree with an intensive major are the same as for the standard program. Ten courses are required beyond the prerequisites, including the senior project. Students must take a mathematics course at the level of, or more advanced than, PHYS 301. Five courses at the core of the major involve advanced study of fundamental topics common to all branches of physics. Three of the courses pertain to advanced classical physics: mechanics (PHYS 410), statistical physics and thermodynamics (PHYS 420), and electromagnetism (PHYS 430). Two other courses incorporate quantum mechanics (PHYS 440 and 441). These courses must be taken in order because the ideas build progressively: PHYS 410 precedes 440, which precedes 441, 420, and 430.

Because experiment is at the heart of the discipline, the intensive major requires one term of advanced laboratory (PHYS 382L or equivalent) and at least two terms of independent research (PHYS 471, 472 or equivalent). One advanced elective course is required to complete the program. Suitable advanced courses include the PHYS 340-level electives and 400-level courses in Physics. Students may also find suitable advanced courses in other departments in the sciences, engineering, and mathematics. Courses taken to satisfy these requirements must be approved by the director of undergraduate studies. In order to pursue their individual interests in sufficient depth, many students choose to take more than ten advanced courses.
Senior requirement for the B.S. degree program, intensive major  The senior requirement for the intensive major is fulfilled by receiving a passing grade on a two-term research project in PHYS 471, 472 or equivalent. Students should consult the director of undergraduate studies for further information.

Sequence of courses  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 freshman 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:

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<th>Freshman or Sophomore</th>
<th>Sophomore or Junior</th>
<th>Senior</th>
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<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>
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<td>PHYS 205L</td>
<td>PHYS 301</td>
<td>PHYS 471 or 472</td>
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<tr>
<td>Mathematics corequisites</td>
<td>PHYS 401</td>
<td>Two advanced electives</td>
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<td>PHYS 402</td>
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<td>PHYS 441</td>
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<td>PHYS 205L</td>
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<td>PHYS 410</td>
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<td>PHYS 382L</td>
<td>One advanced elective</td>
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Approval of programs  All Physics majors in the sophomore, junior, and senior classes must have their programs approved by the director of undergraduate studies. Freshmen and undeclared sophomores who are interested in Physics or related majors are encouraged to meet with the director of undergraduate studies to discuss their questions and proposed programs.

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

Courses

* PHYS 100a / APHY 100a / ENAS 100a / EVST 100a / G&G 105a, 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 Classes*v2 (http://classesv2.yale.edu).  QR, SC

* PHYS 112a / EENG 112, Practical Electronics  Stephen Irons
  Basic theory and practical applications of electricity and electronics, with an emphasis on useful and creative applications. The basic laws of electricity, household electricity and its generation, passive and active electrical components, simple circuit design, and programmable microprocessors and the Arduino platform. Students design, build, and analyze simple electronic devices.  SC

* PHYS 115b / HUMS 455b / THST 115b, 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.  QR, HU, SC
* 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.  SC

PHYS 165La and PHYS 166Lb, 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.  SC  ½ Course cr per term

* 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, kinematics, Newton’s laws of motion, oscillations and waves, gravitation, elasticity, statics, diffusion, fluids, and thermodynamics. Spring-term topics include electricity and magnetism, circuits, light and optics, sound, and modern physics. Essential calculus is introduced as needed. Completion of MATH 112, 115 recommended prior to enrollment. May be taken concurrently with MATH 112, 115.  QR, SC

PHYS 180a and PHYS 181b, University Physics  Staff
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.  QR, SC

PHYS 200a and PHYS 201b, Fundamentals of Physics  Helen Caines and Francis Robinson
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.  QR, SC

PHYS 205La or b and PHYS 206La or b, Modern Physical Measurement  Karsten Heeger and 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.  SC  ½ Course cr per term

* 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.  QR, SC

PHYS 295a / ASTR 255a, Research Methods in Astrophysics  Hector Arce
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. Includes an optional field trip during October recess to the Arecibo 300-meter radio telescope. 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  Corey O’Hern
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&G 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  Priyamvada Natarajan
In-depth discussion of the physics underlying several recent discoveries in astrophysics and cosmology, including extrasolar planets, black holes, and the accelerating universe. Prerequisite: 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 publically 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 382Lb, Advanced Physics Laboratory  
Steve Lamoreaux
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. Prerequisite: PHYS 206L. After or concurrently with PHYS 439 or 440, or with permission of instructor. SC

PHYS 401a and PHYS 402b, Advanced Classical Physics from Newton to Einstein  
Ramanurti Shankar
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  
Witold Skiba
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, Thermodynamics and Statistical Mechanics  
A. Douglas Stone
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. Prerequisites: PHYS 301 and 410 or equivalents. QR, SC

PHYS 428a / AMTH 428a / E&EB 428a / G&G 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  
Francesco Iachello
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  
Robert Schoelkopf
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  
Daisuke Nagai
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  
Sohrab Ismail-Beigi
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  Staff
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

PHYS 478Lb, Computing for Scientific Research  Daisuke Nagai
An introduction to basic computational tools and techniques used in science and engineering research. The fundamentals of PC hardware, the UNIX/Linux operating system, scripting languages (Python), and the development of programs to solve physical and mathematical problems. Programming languages, with emphasis on C/C++ (procedural and object-oriented) as well as the conceptual underlying numerical methods. Intended for students with little basic programming experience.