PHYSICS

haverford.edu/physics

The physics program provides majors with a high level of competency in many facets of physics, including experimental laboratory skills, physical problem-solving, mathematical expertise and scientific computing, in addition to considerable physics content knowledge.

While many of our majors go on to graduate study, we have structured our programs to be sufficiently flexible that they also accommodate students wishing to study abroad, or to combine physics with other fields of study, such as medicine and interdisciplinary programs in astrophysics, biophysics, chemical physics, computing, and engineering. Students can explore these options by selecting either the traditional or interdisciplinary major, which have different requirements. All students receive advanced training in at least three of the foundational areas of physics (including mechanics, electricity and magnetism, thermal and statistical physics and quantum mechanics). We also provide opportunities to participate in original research with faculty members.

LEARNING GOALS

We expect that physics students should be able to solve problems independently in the main areas covered in our curriculum, not only by applying equations straightforwardly to solve standard problems, but also by translating their knowledge into solutions of novel physical scenarios. Students are expected to both gain content knowledge, both conceptual and quantitative, as well as process skills (e.g., the use of mathematical tools such as Fourier analysis, as well as computer methods for solving equations) appropriate for each course. Our laboratories, for instance, require substantial independent hands-on experimental work, teamwork, data analysis and reporting (in the form of a journal article in our advanced laboratories), and oral reporting, to allow the instructor to assess the level of understanding and performance of each student.

CURRICULUM

The department offers a unified coherent curriculum through the first two years, covering mechanics, thermal physics, waves, optics, electricity and magnetism, fluid mechanics, quantum mechanics and special relativity. We provide several different paths to enter the study of physics to accommodate differing levels of preparation and other academic interests. After the second year, we encourage students to select among course options according to their interests, so the actual content of the program can be different for different students. All students receive advanced training in at least three of the foundational areas of physics (including mechanics, electricity and magnetism, thermal and statistical physics and quantum mechanics). We also provide opportunities to participate in original research with faculty members.

We advise prospective majors in all of the science disciplines to study some physics in their first or second year at Haverford, given that all contemporary sciences rely heavily on basic physical principles. There are three different introductory options:

- PHYS 101 and 102 constitute a year-long, self-contained treatment of all of physics, with particular attention to applications in the life sciences.
- PHYS 105 and 106 use calculus somewhat more intensively and are designed for students who expect to continue their study of physics in other courses, in the Physics, Astronomy or Chemistry Departments.
- PHYS 115 (followed by 106) provides a third option, designed for students with advanced preparation. Advice on course selection is provided on the department's web site.

A typical course sequence introducing both the traditional major and the minor consists of PHYS 105 (or 115), 106, 213, 214, and the 211 and 301 laboratories. However, students beginning their study in PHYS 101 and 102 may continue with PHYS 213 and join the major or minor as well.

PHYS 105 (or 115), 106, 213, and 214 are also prerequisites for the astronomy and astrophysics majors; we recommend (but do not require) the half-credit course ASTR/ PHYS 152, which is intended for first-year students considering a physical science major who would like an opportunity to study recent developments in astrophysics.

PHYS 213 and 214 and their associated

laboratories (PHYS 211 and 301) serve as an introduction to waves, electronics, optics, mathematical methods in physics and quantum physics. We also offer a set of 300-level lecture courses covering core areas of physics as well as some topical subjects such as solid state physics and computational astrophysics.

In addition to concentrated study in core areas of physics, such as statistical physics and quantum mechanics, the department emphasizes student participation in research with faculty members. Currently, we have active research programs in soft condensed matter and granular physics, astroparticle and early Universe physics, extragalactic astronomy, gravity wave physics, biological physics, and nanoscience. Courses numbered PHYS 412 to 415 and ASTR 404 provide majors with opportunities to participate in these research efforts for academic credit during their senior year. Paid summer research positions are often available.

Advanced students interested in teaching may participate in the instructional program by registering for PHYS 459 or 460. (Students interested in physics or science education at the secondary level should also consult the teaching certification information in the section on Education and Educational Studies.)

MAJOR REQUIREMENTS

Physics offers three distinct programs: a traditional major, an interdisciplinary major designed to accommodate a focused plan of study in a different field, and a minor. The requirements for these three options are listed below.

Traditional Physics Major Requirements

- PHYS 105 (or 101 or 115), 106 (or 102), 213, 214, 211, and 301 (or Bryn Mawr equivalents). Students may take the last two concurrently with 213 and 214.
- MATH 121 (or 216) and 215 (or one of: MATH 222, the Bryn Mawr equivalent of MATH 215, another 200-level mathematics course with permission).
- Six upper-level courses from the Physics and Astronomy departments at Haverford or Bryn Mawr.
  - One of these must be a laboratory course such as PHYS 326 or Bryn Mawr 305.
  - Majors must take three of the four core theoretical courses: PHYS 302, 303, 308, and 309.
  - One of the six upper-level physics courses may be a 400-level research course.
  - Majors may count either PHYS 459 or 460 among the six upper-level courses.
  - Majors must take one course outside physics, at a level consistent with the student's background, in astronomy, biology, computer science, chemistry, engineering (at Penn or Swarthmore) or mathematics (beyond those courses required for the major). (This requirement is waived for double majors.)
- PHYS 399, including a presentation and senior paper based on independent work, and attendance at senior colloquia and distinguished lectures hosted by the department.

Students may replace two of the six upper-level courses by upper-level courses in a related department, with the approval of the major advisor. (The department asks students to prepare a brief written statement explaining the relationship between the proposed courses and the physics major.)

Students considering graduate study in physics should take four of the following five courses by the end of their junior year: 302, 303, 308, 309, and 326 (or their Bryn Mawr equivalents).

Interdisciplinary Physics Major Requirements

We encourage students with multiple academic interests who are not likely to undertake physics graduate study to consider the interdisciplinary physics major, with a slightly abbreviated set of requirements students can complete in three years. The interdisciplinary major differs from the traditional physics major by offering more flexible course choices and by coordinating the physics courses with the student's work in another field. In the version requiring the fewest physics courses, this major requires 8.5 instead of 12 physics courses, while both majors require 2 math courses, and 3 courses in a related field.

Students can discuss this track—which can also facilitate a concentration, an engineering option, or a minor in another department—with any member of the department.

The requirements are as follows:

- Either PHYS 105 (or 115) and 106, or PHYS 101 and 102.
- PHYS 213 and 214 (our sophomore lecture course sequence) and PHYS 211 (sophomore-level laboratory course).
- MATH 121 (or 216) and 215 (or one of: MATH 222, the Bryn Mawr equivalent of MATH 215, another 200-level mathematics course with permission).
- Three 300-level physics lecture courses, two of which must be drawn from these core courses: PHYS 302, 303, 308, and 309.
- An upper-level laboratory course in the natural or applied sciences, such as PHYS 301, ASTR 341A, BIOL 300A or B, or CHEM 301 or 302. (Alternately, the student can request the substitution of an advanced laboratory course in another area of science or applied science.)
- Two other courses, at the 200 level or higher in a related field, that are part of a coherent program, which the student proposes and the major advisor must approve.
- Senior Seminar (PHYS 399) and the associated senior talk and thesis.

MINOR REQUIREMENTS

- PHYS 105 (or 101 or 115) and PHYS 106 (or 102); PHYS 213, 214, 211 and PHYS 301 labs (or Bryn Mawr equivalents).
- MATH 121 (or 216) and MATH 215 (or one of: MATH 222, the Bryn Mawr equivalent of MATH 215, another 200-level mathematics course with permission).
- One of the four "core" 300-level lecture courses in physics at Haverford or Bryn Mawr: PHYS 302 (Advanced Quantum Mechanics), 303 (Statistical Physics), 308 (Advanced Classical Mechanics), or 309 (Advanced Electromagnetism and Modern Optics).
- Participation for two semesters in the public lectures and seminars hosted by the department.

SENIOR PROJECT

The senior research program demonstrates achievement in depth in a particular subfield of physics or astrophysics. Students participate in PHYS 399, a year-long, ½ credit senior seminar. We assess students by their performance on a short talk during the fall semester, a comprehensive talk or poster presentation in the spring semester and a senior thesis (typically 25-50 pages, including figures and references), written in the form of a scientific paper.

In addition, as part of the year-long senior seminar, senior physics majors study topics in scientific integrity in two student-led meetings, using readings and role-playing scenarios to learn best practices in the ethical conduct of research. They also receive training in life after Haverford, including how to choose and apply to graduate schools, and what careers are available outside science for physics majors.

Students are expected to place their senior research work in the context of the scientific literature in their field of study, and to present their results to an audience of professionals (for their thesis) and their peers (for the talk or poster). They are given training in searching and reading the scientific literature by each research supervisor, as well as specific materials through the senior seminar course.

Most students also take a senior research course for credit (though this is not required). Their work in this course also assesses their research accomplishments. The precise expectations and standards are necessarily different for theoretical and experimental research, and for each specific subfield of physics. However, a useful standard is that student theses ought to be comparable in quality to student-published works in the American Journal of Physics.

Senior Project Learning Goals

We expect senior research in physics to demonstrate:

- a clear understanding of the scientific context of the research (including a review of the relevant scientific literature).
- mastery of the content and findings of the research.
- independent problem solving and ability to synthesize material.
- an understanding of the forward looking implications of the research findings.
- clarity in the public presentation of the research.

Senior Project Assessment

The evaluation of students' overall work in the senior seminar includes both their content knowledge in their research area, and their ability to communicate this work. In the fall semester, students write up the introduction and background sections of their senior thesis while getting training in researching and reading the scientific literature and properly referencing their bibliographic sources. They receive formative assessment from their senior thesis advisor on the fall paper, including suggestions for improvements on the final thesis. For the senior thesis, there are multiple rounds of assessment, since students get ongoing feedback from their research supervisors while writing their thesis, and they submit two distinct formal drafts which are read carefully by two faculty members who give extensive feedback. After each round, students must respond to this feedback while preparing their final thesis.

Similarly, each student gives a first short (10 minute) research talk in the fall and is given department-wide comments about how to improve this talk before they prepare and give their final senior presentation. Typically, each student practices each presentation several times, receiving detailed feedback from a supervisor in between to ensure they present their work at a level comparable with that of poster presentations and short talks at the American Physical Society or other comparable annual meetings.

The thesis research itself is evaluated for (i) a demonstrated understanding of the context and content of the research (including a review of the relevant scientific literature), (ii) independent problem solving and synthesis, and (iii) success in understanding the forward looking implications of the research.

The written and oral presentations of the research are evaluated for (i) a clear and appropriate writing style and (ii) well-curated visual displays of the research.

A further confirmation of quality is the number of senior research projects that lead to publication in a peer-reviewed scientific journal.

REQUIREMENTS FOR HONORS

The departmental awards for honors in physics are based on the quality of performance in course work and the senior colloquium and paper. High honors carries the additional requirement of demonstrated originality in senior research.

CONCENTRATIONS AND INTERDISCIPLINARY MINORS

Physics majors can pursue a concentration in scientific computing.

Physics majors with biological interests may also qualify for the biophysics concentration.

Physics majors may also take an area of concentration in education.

Each of these concentrations is described in its relevant section of the Catalog.

AFFILIATED PROGRAMS

Students interested in engineering can complete an individualized major program in preparation for graduate work in engineering or the Engineering 4+1 Program with the University of Pennsylvania or the 3/2 Program with Caltech; for details see the Engineering section. Students interested in materials science should also consult the related offerings in materials chemistry through Haverford's Department of Chemistry.

STUDY ABROAD

Physics majors can and do pursue studies abroad. There are a number of programs, mostly in English-speaking countries, that allow physics majors to continue and broaden their studies in the field while abroad.

FACILITIES

See the departmental web page for a description of laboratories, equipment and other special facilities for this program.

FACULTY

Theodore Brzinski
Assistant Professor

Daniel Grin
Assistant Professor

Suzanne Amador Kane
Chair & Professor

Andrea Lommen
Professor

Karen Masters
Associate Professor

Bruce Partridge
Bettye and Howard Marshall Professor of Natural Sciences and Professor of Astronomy Emeritus

Kevin Setter
Visiting Assistant Professor

Walter Smith
The Paul and Sally Bolgiano Professor of Physics

Paul Thorman
Laboratory Instructor

COURSES

PHYS H101 CLASSICAL AND MODERN PHYSICS I

Suzanne Amador Kane
Natural Science (NA), Quantitative (QU)
Three class hours and one laboratory period. The first of a two-semester comprehensive introduction to physics, with an emphasis on life science applications involving Newtonian mechanics, oscillations, mechanics of materials, fluids, and thermal physics. Prerequisite(s): Calculus at the level of MATH H105 or equivalent should be taken prior to or concurrently with this course. (Offered Fall 2017)

PHYS H102 CLASSICAL AND MODERN PHYSICS II

Staff
Natural Science (NA), Quantitative (QU)
The second of a two-semester comprehensive introduction to physics, with an emphasis on life science applications involving electricity and magnetism, waves, electronics, waves and optics. Three class hours and one laboratory period. Prerequisite(s): PHYS H101 and MATH H105 or equivalent. (Offered Spring 2018)

PHYS H105 FUNDAMENTAL PHYSICS I

Daniel Grin
Natural Science (NA), Quantitative (QU)
Three class hours and one laboratory period. Newtonian mechanics and thermodynamics. Applications are drawn primarily from the physical sciences. This sequence (105/106) is meant as a one-year introduction suitable for students interested in the physical sciences. Prerequisite(s): MATH H118 or equivalent. (Offered Fall 2017)

PHYS H106 FUNDAMENTAL PHYSICS II

Staff
Natural Science (NA), Quantitative (QU)
Electricity and magnetism, optics, electronics and special relativity. Applications are drawn primarily from the physical sciences. This sequence (105/106) is meant as a one -year introduction suitable for students interested in the physical sciences. Three class hours and one laboratory period. Prerequisite(s): MATH H118 and PHYS H105 or equivalent. (Offered Spring 2018)

PHYS H115 MODERN INTRODUCTORY PHYSICS: BEYOND NEWTON

Theodore Brzinski
Natural Science (NA), Quantitative (QU)
This introductory course provides students who have an advanced background in mechanics with an alternative pathway into physics by exploring applications of introductory physics through a modern perspective. Examples will be drawn from topics such as quantum physics, materials and nanoscience, biophysics, chaos and fluid motion, and relativity. This course forms a year-long sequence with PHYS 106: Fundamental Physics II (Electricity and Magnetism) in the spring semester. Three class hours and one laboratory period. Prerequisite(s): Advanced placement by the physics department and MATH H118 or equivalent. (Offered Fall 2017)

PHYS H152 FIRST-YEAR SEMINAR IN ASTROPHYSICS

Staff
Natural Science (NA)
This half-credit course is intended for prospective physical science majors with an interest in recent developments in astrophysics. Topics in modern astrophysics will be viewed in the context of underlying physical principles. Topics include black holes, quasars, neutron stars, supernovae, dark matter, the Big Bang, and Einstein's relativity theories. Crosslisted: Astronomy, Physics Prerequisite(s): PHYS H101 or H105 and concurrent enrollment in PHYS H102 or H106 (or Bryn Mawr equivalents). (Offered Spring 2018)

PHYS H211 LABORATORY IN ELECTRONICS, WAVES AND OPTICS

Suzanne Amador Kane
Natural Science (NA)
The first half of this laboratory is an introduction to analog electronics and instrumentation. The second half includes experiments in waves and optics. Corequisite(s): PHYS H213 must either be taken concurrently or as a prerequisite. (Offered Fall 2017)

PHYS H213 WAVES AND OPTICS
Daniel Grin
Natural Science (NA)
Vibrations and waves in mechanical, electronic, and optical systems with an introduction to related mathematical methods such as functions of a complex variable and Fourier analysis. Topics include free and driven oscillations, resonance, superposition, coupled oscillators and normal modes, traveling waves, Maxwell's equations and electromagnetic waves, interference, and diffraction. PHYS H211, a related laboratory half-course, is normally taken concurrently and is required for majors. Prerequisite(s): PHYS H106 and MATH H118 or equivalent. (Offered Fall 2017)

PHYS H214 INTRODUCTORY QUANTUM MECHANICS
Walter Smith
Natural Science (NA)
Introduction to the principles governing systems at the atomic scale. Topics include the experimental basis of quantum mechanics, wave-particle duality, Schrodinger's equation and solutions in one dimension, time dependence of quantum states, angular momentum, and one-electron atoms. Recent developments, such as paradoxes calling attention to the remarkable behavior of quantum systems, or quantum computing, will be discussed. Multi-electron atoms and nuclei will be considered if time allows. We recommend taking Physics 301, a related laboratory half-course, concurrently. Prerequisite(s): PHYS H213 or PHYS B308; we strongly recommend taking MATH H215 (Linear Algebra) or the equivalent before PHYS 214. (Offered Spring 2018)

PHYS H301 QUANTUM PHYSICS LABORATORY
Theodore Brzinski
Natural Science (NA)
A full-semester weekly laboratory focusing on experiments of modern relevance with a focus on quantum mechanics. Topics may include: how lasers work and laser spectroscopy; spin resonance; nuclear and cosmic ray physics; electron diffraction; photoelectric effect; superconductivity; quantum eraser (a "which way" experiment); and others. This is one of two laboratories at the advanced level required for the regular physics major and fulfills the advanced laboratory requirement for the interdisciplinary physics major. Prerequisite(s): PHYS H211; Co-requisite: PHYS 214. (Offered Spring 2018)

PHYS H302 ADVANCED QUANTUM MECHANICS
Daniel Grin
Natural Science (NA)
A continuation of the study of quantum mechanics begun in 214. Topics include matrix mechanics and spin, many-particle systems, perturbation theory and scattering theory. A variety of physical systems will be treated as examples, such as simple atoms, neutrino oscillations, and solids. Prerequisite(s): PHYS 214 and either PHYS H213 or PHYS B306. (Typically offered every other spring)

PHYS H303 STATISTICAL PHYSICS
Theodore Brzinski
Natural Science (NA)
Treatment of many body systems using classical and quantum statistics and ensembles to derive the laws of thermodynamics and statistical mechanics. This course includes applications to the thermal properties of matter (solids, liquids and gases), photon, and phonon systems. Prerequisite(s): PHYS 214 and either PHYS H213 or PHYS B306. (Offered Fall 2017)

PHYS H304 COMPUTATIONAL PHYSICS
Daniel Grin
Natural Science (NA)
An introduction to the methods and problems of computational physics, including matrix methods, ordinary differential equations, integration, eigensystems, Monte Carlo techniques, Fourier analysis, and iterative methods. Course will include a substantial independent project.
Crosslisted: Physics, Astronomy, Computer Science; Prerequisite(s): CMSC H105 (or equivalent) and either PHYS H213 or PHYS B306. (Offered Spring 2018)

PHYS H308 MECHANICS OF DISCRETE AND CONTINUOUS SYSTEMS
Daniel Grin
Natural Science (NA)
Classical mechanics of systems of particles, conservation laws, Lagrangian mechanics, motion in central potentials, and core elements of chaos/non-linear dynamics. Fluid mechanics, covering the assumptions of the fluid approximation, key conservation laws, laminar, creeping, turbulent flow, and special topics like

convection, waves, vortices, rotating flows, instabilities, flight, and biological flows as time and interest permit. Prerequisite(s): Either PHYS H213 or PHYS B306. (Typically offered every other fall)

PHYS H309 ADVANCED ELECTROMAGNETISM
Daniel Grin
Natural Science (NA)
Boundary value problems, multipole fields, dielectric and magnetic materials; electromagnetic waves, propagation in dielectric media, conductors and waveguides; gauge transformations, radiating systems. Prerequisite(s): PHYS 214 and either PHYS H213 or PHYS B306. (Offered Spring 2018)

PHYS H320 TOPICS IN BIOLOGICAL PHYSICS: BIOMECHANICS & SENSORY ECOLOGY
Suzanne Amador Kane
Natural Science (NA)
A survey of physical methods used to study problems in human, animal and plant biomechanics and sensory ecology. The class will be run seminar-style and will include student-led discussions of readings in a textbook and in the research literature. Assignments will include problem sets, laboratories and a final modeling or experimental project exploring a topic of the student's choice. Prerequisite(s): MATH H121 and at least two 200-level courses in either physics or biology. (Offered Spring 2018)

PHYS H322 SOLID STATE PHYSICS
Walter Smith
Natural Science (NA)
Understanding solid materials using the principles of quantum and statistical physics. Topics include crystal structure, vibrations in crystals, electron conduction in metals and semiconductors, and electronic devices. Typically offered yearly in alternation with Bryn Mawr. Prerequisite(s): PHYS 214 and either PHYS H213 or PHYS B306. (Typically offered every other year)

PHYS H326 ADVANCED PHYSICS LABORATORY
Walter Smith
Natural Science (NA)
Design, execution, and analysis of significant experiments, including experiments on fundamental techniques such as low-noise electronic measurements, optics, and computer interfacing, as well as more advanced experiments which change from year to year. These include studies of microfluidics, atomic spectroscopy, cosmic ray physics, superconductivity, sensor technologies, and chaotic dynamics. Prerequisite(s): PHYS H301, PHYS 214 and either PHYS H213 or PHYS B306. (Offered Fall 2017)

PHYS H399 SENIOR SEMINAR
Staff
Natural Science (NA)
A capstone experience for seniors in physics and astrophysics meeting biweekly throughout the year. An introduction to scientific writing and speaking; scientific ethics; graduate study in physics and astronomy; career options for physics and astronomy majors, both within the field and outside science; preparation and presentation of senior papers and colloquia; attendance at lectures by distinguished visitors; and discussions of student and faculty research projects in the department. Prerequisite(s): Senior standing in physics or astrophysics. (Offered Fall 2017 and Spring 2018)

PHYS H411 RESEARCH IN SOFT MATTER PHYSICS
Theodore Brzinski
Natural Science (NA)
Experimental research studying the rigidity and failure of jammed, disordered solids, and the mechanical response of athermal and nonlinear materials. Prerequisite(s): Instructor consent. (Offered Fall 2017 and Spring 2018)

PHYS H412 RESEARCH IN THEORETICAL AND COMPUTATIONAL PHYSICS
Daniel Grin
Natural Science (NA)
Independent research on current problems in theoretical physics, with emphasis on the physics of condensed matter systems; extensive use is made of computer-based methods. Prerequisite(s): Instructor consent. (Offered Fall 2017 and Spring 2018)

PHYS H413 RESEARCH IN BIOLOGICAL PHYSICS
Suzanne Amador Kane
Natural Science (NA)
Experimental & computational research applying physics to problems in biomechanics, animal behavior & sensory ecology. Prerequisite(s):

Instructor consent. (Offered Fall 2017 and Spring 2018)

PHYS H415 RESEARCH IN NANOSCALE PHYSICS
Walter Smith
Natural Science (NA)
Research on the morphology and electronic properties of nano-scale materials. Advanced lab experience preferred. Prerequisite(s): Instructor consent. (Offered Fall 2017 and Spring 2018)