PHYSICS

**Director of undergraduate studies:** Nikhil Padmanabhan (nikhil.padmanabhan@yale.edu), Thomas Mellon Evans Hall, Rm. 207, 56 Hillhouse Ave., 432-9960; physics.yale.edu/academics/undergraduate-studies

The overarching goal of the physics program is to train students—majors and nonmajors alike—to think like physicists, the hallmarks of which include: striving for fundamental explanations that have broad predictive power; appreciating that quantitative analysis is necessary for proper understanding; simplifying physical situations to their essentials to enable the development of mathematical models to explain and predict experimental data; and comparing experimental data from the natural world to theory.

To achieve this goal, we offer courses for physics majors who intend to further their study of physics or any STEM field in graduate school, as well as those physics majors who intend to go into law, consulting, financial services, technology industries, teaching, or any number of fields. Many students enroll in our introductory courses as a compulsory requirement of their STEM major; to satisfy a requirement for admission into medical school; or because they appreciate the quantitative training and intrinsic value offered by a basic understanding of modern physics. The director of undergraduate studies (DUS) can help students prepare for graduate school in physics by recommending appropriate electives to supplement the core courses. Research experience (PHYS 469, 470, 471, and 472) is an important aspect of preparing for graduate school.

The department offers two majors in Physics: the B.S. and the B.S. 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 interests. Both degree programs require some research experience. PHYS 469 and PHYS 470, introductory research courses, are open to all students. Juniors and seniors, as part of the senior requirement, are required to enroll in PHYS 471 and 472—one term for the B.S. degree and two terms for the B.S. degree, intensive major. Combined majors are available in Mathematics and Physics, Astrophysics, Physics and Philosophy, and Physics and Geosciences.

**COURSES FOR NONMAJORS AND MAJORS**

A guide to selecting physics courses 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. Many of these courses fulfill the science and/or quantitative reasoning distributional requirements. 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 are interested in the biological sciences or medicine. Knowledge of differential and integral calculus at the level of MATH 112 or equivalent is a prerequisite. MATH 115 or (preferably) MATH 116 should be taken concurrently with PHYS 171. PHYS 170 is a prerequisite for PHYS 171.
2. PHYS 180, 181 is aimed at students who plan to major in the physical sciences or engineering. Calculus at the level of MATH 112 is a prerequisite; MATH 115 and 120 should be taken concurrently. PHYS 180 or PHYS 200 is a prerequisite for PHYS 181.
3. PHYS 260, 261 is intended for students who have had excellent prior training in mathematics and a solid foundation in physics. One of MATH 120, ENAS 151, PHYS 301, or the two-course sequence MATH 230, 231, or the 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 engineering, the life 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 or engineering. 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 2020–2021 include PHYS 341, PHYS 343, and PHYS 344.

**PREREQUISITES**

**B.S. degree program** The prerequisites include 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 222 or 225; 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 first 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 first year at the appropriate level.

**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.

**REQUIREMENTS OF THE MAJOR**

**B.S. degree program** 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, PHYS 401, 402, and either PHYS 439 or 440, involve advanced study of fundamental topics common to all branches of physics. PHYS 401 and 402 pertain to advanced classical physics (mechanics, statistical physics and thermodynamics, and electromagnetism), while the third, PHYS 439 or 440 covers quantum mechanics. PHYS 401 must be taken before PHYS 402, 439, or 440.

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 DUS. In order to pursue their individual interests in sufficient depth, many students choose to take more than the required number of advanced courses.

**B.S. degree program, intensive major** 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). Because the ideas build progressively: PHYS 410 must precede PHYS 440; PHYS 440 must precede PHYS 441, 420, and 430; and PHYS 430 must precede PHYS 441.

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 DUS. In order to pursue their individual interests in sufficient depth, many students choose to take more than ten advanced courses.

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

**Roadmap** See visual roadmap of the requirements.

**SENIOR REQUIREMENT**

**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. One enrollment of PHYS 471 or 472 taken anytime junior or senior year counts as the senior requirement for the Physics major. Students should consult the DUS for further information.

**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 or 472. Two enrollments of PHYS 471 or 472 taken anytime junior or senior year counts as the senior requirement for the intensive Physics major. Students may take either PHYS 471 or 472 two times or they can take each course one time. Students should consult the DUS for further information.

**ADVISING**

All Physics majors in the sophomore, junior, and senior classes must have their programs approved by the DUS. 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>
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</thead>
<tbody>
<tr>
<td>PHYS 170, 171, or 180, 181, or 200, 201, or 260, 261</td>
<td>PHYS 206L</td>
<td>PHYS 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>
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</tbody>
</table>
A program for a student completing the intensive major in three years might be:

<table>
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<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>PHYS 441</td>
</tr>
<tr>
<td>PHYS 205L</td>
<td>PHYS 301</td>
<td>PHYS 420</td>
</tr>
<tr>
<td>Mathematics corequisites</td>
<td>PHYS 410</td>
<td>PHYS 430</td>
</tr>
<tr>
<td>PHYS 440</td>
<td>PHYS 401</td>
<td>PHYS 471</td>
</tr>
<tr>
<td>PHYS 382L</td>
<td>PHYS 410</td>
<td>PHYS 472</td>
</tr>
<tr>
<td>One advanced elective</td>
<td></td>
<td></td>
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</tbody>
</table>

REQUIREMENTS OF THE MAJOR

B.S. DEGREE
Prerequisites PHYS 170, 171 or 180, 181 or 200, 201 or 260, 261, with appropriate math coreqs, as indicated; 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 PHYS 439 or 440, as indicated
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, as indicated; PHYS 382L or equivalent
Distribution of courses 1 advanced elective approved by DUS
Senior requirement two terms of PHYS 471 or 472

The overarching goal of the physics program is to train students—majors and nonmajors alike—to think like physicists, the hallmarks of which include: striving for fundamental explanations that have broad predictive power; appreciating that quantitative analysis is necessary for proper understanding; simplifying physical situations to their essentials to enable the development of mathematical models to explain and predict experimental data; and comparing experimental data from the natural world to theory.

To achieve this goal, we offer courses for physics majors who intend to further their study of physics or any STEM field in graduate school, as well as those physics majors who intend to go into law, consulting, financial services, technology industries, teaching, or any number of fields. Many students enroll in our introductory courses as a compulsory requirement of their STEM major; to satisfy a requirement for admission into medical school; or because they appreciate the quantitative training and intrinsic value offered by a basic understanding of modern physics. The director of undergraduate studies (DUS) can help students prepare for graduate school in physics by recommending appropriate electives to supplement the core courses. Research experience (PHYS 469, 470, 471, and 472) is an important aspect of preparing for graduate school.

COURSES WITH NO CALCULUS REQUIREMENT
These courses are designed for non–science students with little or no background in physics. None has a college-level mathematics requirement. Each course may count toward the distributional requirements in science and/or quantitative reasoning. Expected offerings for 2020–2021 include:

COURSE LIST
PHYS 110, Developments in Modern Physics
PHYS 112, Practical Electronics
PHYS 120, Quantum Physics and Beyond

CALCULUS-BASED INTRODUCTORY PHYSICS LECTURE COURSES
The four introductory physics course sequences listed below are calculus-based. Students should have the appropriate background in mathematics to take these courses. Completion of an introductory sequence also prepares students for a series of 340-level electives, which cover special topics of interest to both majors and nonmajors.

For more details, please see the Guide to Selecting the Best Physics Course for You.

- PHYS 170 and PHYS 171 are for students who are interested in the medical and biological sciences. Knowledge of differential and integral calculus at the level of MATH 112, or equivalent is a prerequisite for PHYS 170 and PHYS 171. PHYS 170 is a prerequisite for PHYS 171. MATH 115 should be taken concurrently with PHYS 171.
- PHYS 180 and PHYS 181 are 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; PHYS 180 or PHYS 200 is a prerequisite for PHYS 181. MATH 115 and MATH 120 should be taken concurrently.
• PHYS 200 and PHYS 201 are 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 225 or MATH 222, are generally taken concurrently.
• PHYS 260 and PHYS 261 are for students who have excellent training in physics and mathematics and a flair for mathematical methods and quantitative analysis. One of the following: MATH 120, ENAS 151, PHYS 301, or the two-term sequence MATH 230 and MATH 231, or the equivalent should be taken concurrently.

LABORATORY COURSES
• PHYS 165L and PHYS 166L do not require a strong high school physics laboratory preparation. Related lecture courses are PHYS 170, PHYS 171, or PHYS 180.
• PHYS 205L and PHYS 206L are for students who plan to major in the physical sciences or engineering. The related lecture courses are PHYS 180, PHYS 181, or PHYS 200, PHYS 201, or PHYS 260, PHYS 261. Students are advised to start this laboratory sequence in the spring of the first year or the fall of the sophomore year.

The following table summarizes some important information about the lecture and laboratory courses described above.

<table>
<thead>
<tr>
<th>Course Combination</th>
<th>Meets Medical School Requirement</th>
<th>Acceptable for Physics Major</th>
<th>Math Taken Concurrently</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHYS 050–PHYS 120</td>
<td>no</td>
<td>no</td>
<td>none</td>
</tr>
<tr>
<td>PHYS 170, PHYS 171</td>
<td>yes</td>
<td>yes</td>
<td>MATH 115</td>
</tr>
<tr>
<td>PHYS 180, PHYS 181</td>
<td>yes</td>
<td>yes</td>
<td>MATH 115, MATH 120</td>
</tr>
<tr>
<td>PHYS 200, PHYS 201</td>
<td>yes</td>
<td>yes</td>
<td>MATH 120, and MATH 222 or MATH 225</td>
</tr>
<tr>
<td>PHYS 260, PHYS 261</td>
<td>yes</td>
<td>yes</td>
<td>One of MATH 120, ENAS 151, PHYS 151, MATH 230 and MATH 231, or PHYS 301, or equivalent in multivariable calculus</td>
</tr>
</tbody>
</table>

| PHYS 165L, PHYS 166L | yes                              | yes                          |
| PHYS 205L, PHYS 206L  | yes                              | yes                          |

Further information about undergraduate physics at Yale can be found on the department website.

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, Sarah Demers, David DeMille, †Michel Devoret, †Debra Fischer, Bonnie Fleming, †Marla Geha, Steven Girvin, Larry Gladney, Leonid Glazman, John Harris, Karsten Heeger, †Victor Henrich, †Jonathon Howard, Francesco Iachello (Emeritus), †Sohrab Ismail-Beigi, Steven Lamoreaux, Simon Mochrie, Vincent Moncrief, †Priyamvada Natarajan, †Corey O’Hern, Peter Parker (Emeritus), †Daniel Prober, Nicholas Read, Jack Sandweiss (Emeritus), †Peter Schiffer, †Robert Schoelkopf, Ramamurti Shankar, Witold Skiba, †A. Douglas Stone, †Hong Tang, Paul Tipton (Chair), C. Megan Urry, †Pieter van Dokkum, †John Wettlaufer, Michael Zeller (Emeritus)

Associate Professors  †Murat Acar, Helen Caines, †Damon Clark, †Thierry Emonet, Walter Goldberger, Jack Harris, Reina Maruyama, Daisuke Nagai, Nikhil Padmanabhan, David Poland, †Peter Rakich

Assistant Professors  †Eric Michael Brown, Meng Cheng, Benjamin Machta, David Moore, †John Murray, †Michael Murrell, Nir Navon, Laura Newburgh

Senior Lecturer  Sidney Cahn

Lecturers  Stephen Irons, Rona Ramos, Adriane Steinacker

†A joint appointment with primary affiliation in another department.

View Courses