Physics

Courses offered by the Department of Physics are listed under the subject code PHYSICS on the Stanford Bulletin's ExploreCourses web site (http://exploredegrees.stanford.edu/CourseSearch/search?view=catalog&catalog=&page=0&q=PHYSICS&filter-catalognumber=PHYSICS=on).

Mission of the Undergraduate Program in Physics

The mission of the undergraduate program in Physics is to provide students with a strong foundation in both classical and modern physics. The goal of the program is to develop both quantitative problem solving skills and the ability to conceive experiments and analyze and interpret data. These abilities are acquired through both course work and opportunities to conduct independent research. The program prepares students for careers in fields that benefit from quantitative and analytical thinking, including physics, engineering, teaching, medicine, law, science writing, and science policy, in government or the private sector. In some cases, the path to this career will be through an advanced degree in physics or a professional program.

Learning Outcomes (Undergraduate)

Students develop an understanding of the fundamental laws that govern the universe, and a strong foundation of mathematical, analytical, laboratory, and written communication skills. They will also be presented with opportunities for learning through research. Upon completion of the Physics degree, students should have acquired the following knowledge and skills:

1. A thorough quantitative and conceptual understanding of the core areas of physics, including mechanics, electricity and magnetism, thermodynamics, statistical physics, and quantum mechanics, at a level compatible with admission to graduate programs in physics at peer institutions.
2. The ability to analyze and interpret quantitative results, both in the core areas of physics and in complex problems that cross multiple core areas.
3. The ability to apply the principles of physics to solve new and unfamiliar problems. This ability is often described as "thinking like a physicist."
4. The ability to use contemporary experimental apparatus and analysis tools to acquire, analyze and interpret scientific data.
5. The ability to communicate scientific results effectively in written papers and presentations or posters.

Course Work

The course work is designed to provide students with a sound foundation in both classical and modern physics. Students who wish to specialize in astronomy, astrophysics, or space science should also consult the "Astronomy Program (http://exploredegrees.stanford.edu/ schoolofhumanitiesandsciences/astrophysics)" section of this bulletin.

Three introductory series of courses include labs in which undergraduates carry out individual experiments. The Intermediate and Advanced Physics Laboratories offer facilities for increasingly complex individual work, including the conception, design, and fabrication of laboratory equipment. Undergraduates are also encouraged to participate in research; most can do this through the senior thesis and/or the summer research program.

The study of physics is undertaken by three principal groups of undergraduates: those including physics as part of a general education; those preparing for careers in professional fields that require a knowledge of physics, such as medicine or engineering; and those preparing for careers in physics or related fields, including teaching and research in colleges and universities, research in federally funded laboratories and industry, and jobs in technical areas. Physics courses numbered below 100 are intended to serve all three of these groups. The courses numbered above 100 mainly meet the needs of the third group, but also of some students majoring in other branches of science and engineering.

Entry-Level Sequences in Physics

The Department of Physics offers three year-long, entry-level physics sequences, the PHYSICS 20, 40, and 60 series. The first of these (the 20 series) is non-calculus-based, and is intended primarily for those who are majoring in biology. Students with AP Physics credit, particularly those who are considering research careers, may wish to consider taking the PHYSICS 40 series, rather than using AP placement. These introductory courses provide a depth and emphasis on problem solving that has significant value in biological research, given today's considerable physics-based technology.

For those intending to major in engineering or the physical sciences, or simply wanting a stronger background in physics, the department offers the PHYSICS 40 and 60 series. Either of these satisfies the entry-level physics requirements of any Stanford major. The 60 series is intended for those who have already taken a Physics course at the level of the 40 series, or at least have a strong background in mechanics, some background in electricity and magnetism, and a strong background in calculus.

The PHYSICS 40 series begins with PHYSICS 41 Mechanics in Winter Quarter, PHYSICS 43 Electricity and Magnetism in Spring Quarter, and PHYSICS 45 Light and Heat in Autumn Quarter. While it is recommended that most students begin the sequence with PHYSICS 41 in Winter Quarter, those who have had strong physics preparation in high school (such as a score of at least 4 on the Physics AP C exam) may start the sequence with PHYSICS 45 in Autumn Quarter.

PHYSICS 41A is an optional one-unit companion course to PHYSICS 41 that provides additional problem solving for students with less preparation in math and physics.

The Physics Tutoring Center offers help to students in the Entry-Level courses. It is staffed Monday through Friday. For more detailed schedule and location, see schedule at http://physicstutor.stanford.edu.

Entry-Level Course List

One course from the following is recommended for the humanities or social science student who wishes to become familiar with the methodology and content of modern physics:

<table>
<thead>
<tr>
<th>Subject Code</th>
<th>Course Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHYSICS 15</td>
<td>The Nature of the Universe</td>
<td>3</td>
</tr>
<tr>
<td>PHYSICS 16</td>
<td>Cosmic Horizons</td>
<td>3</td>
</tr>
<tr>
<td>PHYSICS 17</td>
<td>Black Holes</td>
<td>3</td>
</tr>
<tr>
<td>PHYSICS 19</td>
<td>How Things Work: An Introduction to Physics</td>
<td>3</td>
</tr>
</tbody>
</table>

The 20 series (below) is recommended for general students and for students preparing for medicine or biology:

<table>
<thead>
<tr>
<th>Subject Code</th>
<th>Course Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHYSICS 21</td>
<td>Mechanics and Heat</td>
<td>3</td>
</tr>
<tr>
<td>PHYSICS 22</td>
<td>Mechanics and Heat Laboratory</td>
<td>1</td>
</tr>
<tr>
<td>PHYSICS 23</td>
<td>Electricity and Optics</td>
<td>3</td>
</tr>
<tr>
<td>PHYSICS 24</td>
<td>Electricity and Optics Laboratory</td>
<td>1</td>
</tr>
<tr>
<td>PHYSICS 25</td>
<td>Modern Physics</td>
<td>3</td>
</tr>
<tr>
<td>PHYSICS 26</td>
<td>Modern Physics Laboratory</td>
<td>1</td>
</tr>
</tbody>
</table>

The 40 series (below) is for students majoring in engineering, chemistry, earth sciences, mathematics, or physics:
using the tools of Physics. Through completion of advanced course work scholarship and the ability to conduct independent research and analysis studies. This is achieved through completion of courses, in the primary Autumn Quarter. students may normally enter the department only at the beginning of strictly limited. Students should submit applications by Tuesday, December cosmology, accelerator design, and photon science. Opportunities for research are also available with the faculty at SLAC in the Materials Science and Engineering, Electrical Engineering, and Biology. Graduate students find opportunities for research in the fields of astrophysics, particle astrophysics, cosmology, experimental particle physics, particle theory, string theory, intermediate energy physics, low temperature physics, condensed matter physics, materials research, atomic physics, laser physics, quantum electronics, coherent optical radiation, novel imaging technologies, and biophysics. Faculty advisers are drawn from many departments, including Physics, Applied Physics, Materials Science and Engineering, Electrical Engineering, and Biology. Opportunities for research are also available with the faculty at SLAC in the areas of theoretical and experimental particle physics, particle astrophysics, cosmology, accelerator design, and photon science. The 60 series (below), or advanced freshman series, is for students who have had strong preparation in physics and calculus in high school. Students who have had the appropriate background and wish to major in physics should take this introductory series:

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHYSICS 41</td>
<td>Mechanics</td>
<td>4</td>
</tr>
<tr>
<td>PHYSICS 42</td>
<td>Classical Mechanics Laboratory</td>
<td>1</td>
</tr>
<tr>
<td>PHYSICS 43</td>
<td>Electricity and Magnetism</td>
<td>4</td>
</tr>
<tr>
<td>PHYSICS 44</td>
<td>Electricity and Magnetism Lab</td>
<td>1</td>
</tr>
<tr>
<td>PHYSICS 45</td>
<td>Light and Heat</td>
<td>4</td>
</tr>
<tr>
<td>PHYSICS 46</td>
<td>Light and Heat Laboratory</td>
<td>1</td>
</tr>
</tbody>
</table>

The Physics Placement Test

Students who are planning to take either of the calculus-based sequences (PHYSICS 40 or 60 sequence) are advised to take the Physics Placement Test (https://physics.stanford.edu/undergraduate-program/placement-test) that is offered twice at the beginning of the school year: during New Student Orientation and on the evening of the first day of instruction in the Autumn quarter. Advice will be sent to each student with guidance on placement in the 40 or 60 sequence. See this page for details: https://physics.stanford.edu/undergraduate-program/placement-test. Students who do not plan to take the 40 or 60 sequence do not need to take the Placement Test.

Graduate Programs in Physics

Graduate students find opportunities for research in the fields of astrophysics, particle astrophysics, cosmology, experimental particle physics, particle theory, string theory, intermediate energy physics, low temperature physics, condensed matter physics, materials research, atomic physics, laser physics, quantum electronics, coherent optical radiation, novel imaging technologies, and biophysics. Faculty advisers are drawn from many departments, including Physics, Applied Physics, Materials Science and Engineering, Electrical Engineering, and Biology. Opportunities for research are also available with the faculty at SLAC in the areas of theoretical and experimental particle physics, particle astrophysics, cosmology, accelerator design, and photon science. The number of graduate students admitted to the Department of Physics is strictly limited. Students should submit applications by Tuesday, December 16, 2014 for matriculation the following Autumn Quarter. Graduate students may normally enter the department only at the beginning of Autumn Quarter.

Learning Outcomes (Graduate)

The purpose of the master's program is to further develop knowledge and skills in physics and to prepare students for a professional career or doctoral studies. This is achieved through completion of courses, in the primary field as well as related areas, and experience with independent work and specialization.

The Ph.D. is conferred upon candidates who have demonstrated substantial scholarship and the ability to conduct independent research and analysis using the tools of Physics. Through completion of advanced course work and rigorous skills training, the doctoral program prepares students to make original contributions to the knowledge of physics and to interpret and present the results of such research.

Fellowships and Assistantships

The Department of Physics makes an effort to support all its graduate students through fellowships, teaching assistantships, research assistantships, or a combination of sources. More detailed information is provided with the offer of admission.

Laboratories and Institutes

The Russell H. Varian Laboratory of Physics, the Physics and Astrophysics Building, the W. W. Hansen Experimental Physics Laboratory (HEPL), the E. L. Ginzton Laboratory, the Center for Nanoscale Science and Engineering and the Geballe Laboratory for Advanced Materials (GLAM) together house a range of physics activities from general courses through advanced research. Ginzton Lab houses research on optical systems, including quantum electronics, metrology, optical communication and development of advanced lasers. GLAM houses research on novel and nanopatterned materials, from high-temperature superconductors and magnets to organic semiconductors, subwavelength photon waveguides, and quantum dots. GLAM also supports the materials community on campus with a range of characterization tools: it is the site for the Stanford Nanocaracterization Lab (SNL) and the NSF-sponsored Center for Probing the Nanoscale (CPN). The SLAC National Accelerator Laboratory is just a few miles from the Varian Laboratory. SLAC is a national laboratory funded by the Offices of Basic Energy Sciences and High Energy Physics of the Department of Energy. Scientists at SLAC conduct research in photon science, accelerator physics, particle physics, astrophysics and cosmology. The laboratory hosts a two-mile-long linear accelerator that can accelerate electrons and positrons. The Stanford Synchrotron Radiation Light Source (SSRL) uses intense x-ray beams produced with a storage ring on the SLAC site. The Linac Coherent Light Source (LCLS), completed in 2009, is the world's first x-ray free-electron laser and has opened new avenues of research in ultra-fast photon science.

The Kavli Institute for Particle Astrophysics and Cosmology (KIPAC), formed jointly with the SLAC National Accelerator Laboratory, provides a focus for theoretical, computational, observational, and instrumental research programs. A wide range of research areas in particle astrophysics and cosmology are investigated by students, postdocs, research staff and faculty. The two major projects with which KIPAC is heavily involved are the Fermi Gamma-Ray Space Telescope (FSGT) and the Large Synoptic Survey Telescope (LSST). KIPAC members also participate fully in the Cryogenic Dark Matter Search (CDMS), the Solar Dynamics Observatory (SOO), the EXO-200 double beta decay experiment, the Dark Energy Survey (DES), the NuSTAR and Astro-H X-ray satellites, the Cerenkov Telescope Array (CTA) and several cosmic microwave background experiments (BICEP, KECK, QUIET and POLAR-1).

The Ginzton Laboratory, HEPL, GLAM, KIPAC, SLAC, and SSRL are listed in the "Centers, Laboratories, and Institutes (http://exploredegrees.stanford.edu/centers/laboratoriesandinstitutes/researchtext) " section of this bulletin. Students may also be interested in research and facilities at two other independent labs: the Center for Integrated Systems, focused on electronics and nanofabrication; and the Clark Center, an interdisciplinary biology, medicine, and bioengineering laboratory.

The Stanford Institute for Theoretical Physics is devoted to the investigation of the basic structure of matter (particle theory, string theory, M-theory, quantum cosmology, condensed matter physics).

Physics Course Numbering System

Course numbers beyond 99 are numbered in accordance with a three-digit code. The first digit indicates the approximate level of the course:
Bachelor of Science in Physics

To help in deciding which introductory sequence is most suitable, students considering a major in Physics may contact the undergraduate program coordinator (elva@stanford.edu) to arrange an advising appointment. Also see the Physics Placement Test web site (https://physics.stanford.edu/undergraduate-program/placement-test). Although it is possible to complete the Physics major in three years, students who contemplate starting the major during sophomore year should make an advising appointment to map out their schedule. Students who have had previous college-level courses (including EPGY) should make an advising appointment for placement and possible transfer credit. For advanced placement advice, see the Registrar’s web site (http://studentaffairs.stanford.edu/registrar/students/ap).

Prospective Physics majors are advised to take PHYSICS 59 FRONTIERS OF PHYSICS RESEARCH in their freshman or sophomore year.

Required Courses for Majors

All courses for the Physics major must be taken for a letter grade, and a grade of 'C-' or better must be received for all units applied toward the major.

For sample schedules illustrating how to complete the Physics major, see the Department of Physics (https://physics.stanford.edu/undergraduate-program/four-year-plans) web site.

### Required Math Courses (21-23 units)

- **MATH 51** Linear Algebra and Differential Calculus of Several Variables
- or **MATH 51H** Honors Multivariable Mathematics
- **MATH 52** Integral Calculus of Several Variables
- or **MATH 52H** Honors Multivariable Mathematics
- **MATH 53** Ordinary Differential Equations with Linear Algebra
- or **MATH 53H** Honors Multivariable Mathematics
- **MATH 131P** Partial Differential Equations I
- or **MATH 173** Theory of Partial Differential Equations

Plus one advanced mathematics elective (3-5 units)

Select one of the following:
- Any MATH (101 or higher)
- **PHYSICS 112** Mathematical Methods of Physics
- **STATS 116** Theory of Probability
- **EE 261** The Fourier Transform and Its Applications

### Intermediate Sequence

- **PHYSICS 105** Intermediate Physics Laboratory I: Analog Electronics
- **PHYSICS 107** Intermediate Physics Laboratory II: Experimental Techniques and Data Analysis
- **PHYSICS 112** Mathematical Methods of Physics (recommended)
- **PHYSICS 113** Computational Physics (recommended)
- **PHYSICS 120** Intermediate Electricity and Magnetism I
- **PHYSICS 121** Intermediate Electricity and Magnetism II

### Advanced Sequence

- **PHYSICS 108** Advanced Physics Laboratory: Project
- **PHYSICS 110** Advanced Mechanics
- **PHYSICS 130** Quantum Mechanics
- **PHYSICS 131** Quantum Mechanics II
- **PHYSICS 134** Advanced Topics in Quantum Mechanics
- **PHYSICS 170** Thermodynamics, Kinetic Theory, and Statistical Mechanics

---

**Digit** | **Description**
---|---
100 | intermediate and advanced undergraduate courses
200 | first-year graduate courses
300 | more advanced courses
400 | research, special, or current topics

The second digit indicates the general subject matter:

**Digit** | **Description**
---|---
00 | laboratory
10,20,30 | general courses
40 | nuclear physics, nuclear energy, energy
50 | elementary particle physics
60 | astrophysics, cosmology, gravitation
70 | condensed matter physics
80 | optics and atomic physics
90 | miscellaneous courses

### Introductory Sequence

Complete either the 40 Series or the 60 Series

**Units** | **Courses**
---|---
19-20 | PHYSICS 41 Mechanics
| PHYSICS 42 Classical Mechanics Laboratory
| PHYSICS 43 Electricity and Magnetism
| PHYSICS 44 Electricity and Magnetism Lab
| or PHYSICS Introduction to Laboratory Physics 67
| PHYSICS 45 Light and Heat
| PHYSICS 46 Light and Heat Laboratory
| PHYSICS 70 Foundations of Modern Physics

**Units** | **Courses**
---|---
16 | PHYSICS 61 Mechanics and Special Relativity
| PHYSICS 62 Classical Mechanics Laboratory

**Units** | **Courses**
---|---
5 | PHYSICS 63 Electricity, Magnetism, and Waves
| PHYSICS 64 Electricity, Magnetism and Optics Laboratory
| PHYSICS 65 Quantum and Thermal Physics
| PHYSICS 67 Introduction to Laboratory Physics

Physics majors who complete the PHYSICS 60 series must take one additional PHYSICS course numbered 100 or above, selected from this list (3-4 units):

- **PHYSICS 100** Introduction to Observational and Laboratory Astronomy
- **PHYSICS 112** Mathematical Methods of Physics
- **PHYSICS 113** Computational Physics
- **PHYSICS 134** Advanced Topics in Quantum Mechanics
- **PHYSICS 152** Introduction to Particle Physics I
- **PHYSICS 160** Introduction to Stellar and Galactic Astrophysics
- **PHYSICS 161** Introduction to Extragalactic Astrophysics and Cosmology
- **PHYSICS 172** Solid State Physics
- **PHYSICS 211** Continuum Mechanics
- **PHYSICS 216** Back of the Envelope Physics
- **PHYSICS 220** Classical Electrodynamics
- **PHYSICS 230** Quantum Mechanics
- **PHYSICS 231** Quantum Mechanics
- **PHYSICS 262** Introduction to Gravitation

---

Concentrations in Physics

The primary purpose of concentrations in the Physics major is to provide consistent and more formal advising to students who want to concentrate in a particular area of physics during their undergraduate education, or prepare for future graduate studies in a particular area of physics. Physics majors are not required to choose a concentration and a concentration does not add any formal requirements to the Physics major. Upon graduation, students receive a certificate of completion of a concentration.

Students seeking further advice on a given concentration should contact the professor whose name appears next to the respective title of each section below. Within the chosen concentration below, complete at least four courses from the list or three courses plus a senior thesis. No more than one of the courses can be taken for CR/NC.

A. Applied Physics (Hari Manoharan (manoharan@stanford.edu))

- **Solid State**
  - PHYSICS 172 Solid State Physics
  - APPPHYS 270 Magnetism and Long Range Order in Solids
  - MATSCI 195 Waves and Diffraction in Solids

- **Lasers**
  - EE 236A Modern Optics
  - EE 236C Lasers
  - APPPHYS 207 Laboratory Electronics
  - APPPHYS 304 Lasers Laboratory

B. Astrophysics (Roger Romani (rwr@astro.stanford.edu), Sarah Church (schurch@stanford.edu))

- PHYSICS 100 Introduction to Observational and Laboratory Astronomy
- PHYSICS 160 Introduction to Stellar and Galactic Astrophysics
- PHYSICS 161 Introduction to Extragalactic Astrophysics and Cosmology

Select one of the following: 3-4
- PHYSICS 211 Continuum Mechanics
- PHYSICS 260 Introduction to Stellar and Galactic Astrophysics
- PHYSICS 262 Introduction to Gravitation
- PHYSICS 312 Basic Plasma Physics (not offered 2014-15)
- GES 122 Planetary Systems: Dynamics and Origins (offered alternate years, given 2015-16)

C. Biophysics and Medical Physics (Seb Doniach (SXDWG@SLAC.Stanford.Edu))

- BIOC 202 Biochemistry Bootcamp
- BIOPHYS 228 Computational Structural Biology
- BIO 141 Biostatistics
- BIO 217 Neuronal Biophysics (not offered 2014-15)
- BIOE 221 Physics and Engineering of Radionuclide Imaging
- BIOE 222 Instrumentation and Applications for Multi-modality Molecular Imaging of Living Subjects

It is recommended that Physics majors interested in pursuing a career in biophysics consider a minor in Biology.

D. Geophysics (Simon Klemperer (sklemp@stanford.edu))

The following requirements apply to students matriculating 2010-11 or later:

- GEOPHYS 110 Earth on the Edge: Introduction to Geophysics
- GEOPHYS 120 Ice, Water, Fire

Select one of the following:
- GEOPHYS Introductory Seismology
- GEOPHYS Tectonophysics & Global Tectonics
- GEOPHYS Near-Surface Geophysics

E. Theoretical Physics (Andrei Linde (alinde@stanford.edu))

- PHYSICS 152 Introduction to Particle Physics I
- PHYSICS 260 Introduction to Stellar and Galactic Astrophysics
- PHYSICS 262 Introduction to Gravitation
- PHYSICS 330 Quantum Field Theory I
- PHYSICS 331 Quantum Field Theory II
- PHYSICS 332 Quantum Field Theory III
- PHYSICS 351 Standard Model of Particle Physics
- PHYSICS 362 Advanced Extragalactic Astrophysics and Cosmology (not offered 2014-15)
- PHYSICS 364 Advanced Gravitation (not offered 2014-15)

Notes to students taking this concentration:

1. Students should discuss the choice of courses with members of the Institute for Theoretical Physics and/or their major adviser.
2. Students may attend PHYSICS 330 Quantum Field Theory I after taking PHYSICS 130 Quantum Mechanics, PHYSICS 131 Quantum Mechanics II and PHYSICS 134 Advanced Topics in Quantum Mechanics. Prior study of special topics in quantum mechanics (PHYSICS 232, not offered this year) may be helpful.

Senior Thesis

The department offers Physics majors the opportunity to complete a senior thesis. These are the guidelines:

1. Students must submit a Senior Thesis Application form once they identify a physics project, either theoretical or experimental, in...
consultation with individual faculty members. Proposal forms are available from the undergraduate coordinator and must be submitted by the week prior to the Thanksgiving break of the academic year in which the student plans to graduate.

2. Credit for the project is assigned by the adviser within the framework of PHYSICS 205 Senior Thesis Research. A minimum of 3 units of PHYSICS 205 Senior Thesis Research must be completed for a letter grade during the senior year. Work completed in the senior thesis program may not be used as a substitute for regular required courses for the Physics major.

3. A written report and a presentation of the work at its completion are required for the senior thesis. By mid-May, the senior thesis candidate is required to present the project at the department's Senior Thesis Presentation Program. This event is publicized and open to the general public. The expectation is that the student's adviser, second reader, and all other senior thesis candidates attend.

**Honors Program**

Physics majors are granted a Bachelor of Science in Physics with Honors if they satisfy these three requirements beyond the general Physics major requirements:

1. The student files for entry into the Honors Program by completing an Honors Program Application (available from the undergraduate coordinator) by the same deadline as the Senior Thesis Application. Eligibility is confirmed by the department.

2. The student completes a senior thesis by meeting the deadlines and requirements described above.

3. The student completes course work with an overall GPA of 3.30 or higher, and a GPA of 3.50 or higher in courses required for the Physics major.

**Minor in Physics**

The Physics minor allows the student to select a concentration in Physics or Astronomy. The Astronomy concentration has a technical and non-technical option.

All courses for the minor must be taken at Stanford University for a letter grade, and a grade of 'C-' or better must be received for all units applied toward the minor except as noted in the following paragraph.

Students who take the PHYSICS 20, 40, or 60 series at Stanford in support of their major may count those units towards the minor. Those who have fulfilled Physics requirements at the 20 or 40 level by enrollment at another accredited university, or through advanced placement credits, may count credits towards PHYSICS 21, PHYSICS 23, and PHYSICS 24, or PHYSICS 41/PHYSICS 42 and PHYSICS 43/PHYSICS 44.

PHYSICS 25/PHYSICS 26, or PHYSICS 45 /PHYSICS 46 for a minor in Physics or the technical minor concentration in Astronomy, must be taken at Stanford even if similar material has been covered elsewhere.

The minor declaration deadline is three quarters before graduation, typically the beginning of Autumn Quarter if the student is graduating at the end of Spring Quarter.

**Concentration in Physics**

An undergraduate minor in Physics requires a minimum of 25 units with the following course work:

Select one of the following Series:

<table>
<thead>
<tr>
<th>Units</th>
<th>Series A (19 units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHYSICS 41</td>
<td>Mechanics</td>
</tr>
<tr>
<td>&amp; PHYSICS 42</td>
<td>and Classical Mechanics Laboratory</td>
</tr>
</tbody>
</table>

**Series B (16 units)**

<table>
<thead>
<tr>
<th>Units</th>
<th>Series B (16 units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHYSICS 61</td>
<td>Mechanics and Special Relativity</td>
</tr>
<tr>
<td>&amp; PHYSICS 62</td>
<td>and Classical Mechanics Laboratory</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Units</th>
<th>Series C (9-12 units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHYSICS 63</td>
<td>Electricity, Magnetism, and Waves</td>
</tr>
<tr>
<td>&amp; PHYSICS 64</td>
<td>and Electricity, Magnetism and Optics Laboratory</td>
</tr>
</tbody>
</table>

**Units**

<table>
<thead>
<tr>
<th>Units</th>
<th>Series D (9-12 units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHYSICS 65</td>
<td>Quantum and Thermal Physics</td>
</tr>
<tr>
<td>&amp; PHYSICS 67</td>
<td>and Introduction to Laboratory Physics</td>
</tr>
</tbody>
</table>

At least three PHYSICS courses numbered 100 or above from the following courses: PHYSICS 100, 105, 107, 108, 110, 112, 113, 120, 121, 130, 131, 134, 152, 160, 161, 170, 171, 172, 211, 216, 220, 230, 231, or 262.

**Non-Technical**

For students whose majors do not require the PHYSICS 40 or 60 series:

<table>
<thead>
<tr>
<th>Units</th>
<th>Series E (3 units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHYSICS 21</td>
<td>Mechanics and Heat</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Units</th>
<th>Series F (3 units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHYSICS 23</td>
<td>Electricity and Optics</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Units</th>
<th>Series G (4 units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHYSICS 25</td>
<td>Modern Physics</td>
</tr>
<tr>
<td>&amp; PHYSICS 26</td>
<td>and Modern Physics Laboratory</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Units</th>
<th>Series H (3-4 units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHYSICS 50</td>
<td>Astronomy Laboratory and Observational Astronomy</td>
</tr>
</tbody>
</table>

or PHYSICS 100 Introduction to Observational and Laboratory Astronomy

Select two of the following:

<table>
<thead>
<tr>
<th>Units</th>
<th>Series I (6 units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHYSICS 15</td>
<td>The Nature of the Universe</td>
</tr>
<tr>
<td>PHYSICS 16</td>
<td>Cosmic Horizons</td>
</tr>
<tr>
<td>PHYSICS 17</td>
<td>Black Holes</td>
</tr>
</tbody>
</table>

**Technical**

For students whose majors require the PHYSICS 40 or 60 series:
Consist of completing all courses listed below and at least one course from each of two subject areas outside the student’s primary area of research (among biophysics, condensed matter, quantum optics and atomic physics, astrophysics and gravitation, and nuclear and particle physics). For this requirement students must choose from courses numbered above PHYSICS 234, excluding 270, 271, 290, and 294. For a full list of courses by concentration that satisfy the breadth requirement see the Physics Department (https://physics.stanford.edu) website.

The requirements in the following list may be fulfilled by passing the course at Stanford or passing an equivalent course elsewhere:

**Series A**
- PHYSICS 41 Mechanics
- PHYSICS 43 Electricity and Magnetism
- PHYSICS 45 Light and Heat & PHYSICS 46 Light and Heat Laboratory
- PHYSICS 70 Foundations of Modern Physics

**Series B**
- PHYSICS 61 Mechanics and Special Relativity
- PHYSICS 63 Electricity, Magnetism, and Waves
- PHYSICS 65 Quantum and Thermal Physics
- PHYSICS 67 Introduction to Laboratory Physics

And take the following three courses:
- PHYSICS 100 Introduction to Observational and Laboratory Astronomy
- PHYSICS 160 Introduction to Stellar and Galactic Astrophysics
- PHYSICS 161 Introduction to Extragalactic Astrophysics and Cosmology

**Total Units:** 24-28

Students are also encouraged to take the electricity and magnetism/optics lab of the appropriate PHYSICS series, PHYSICS 24, PHYSICS 44 or PHYSICS 64 for 1 additional unit.

### Master of Science

The department does not offer a coterminal degree program, or a separate program for the M.S. degree, but this degree may be awarded for a portion of the Ph.D. degree work.

University requirements for the master’s degree, discussed in the "Graduate Degrees (http://exploredegrees.stanford.edu/graduatedegrees) " section of this bulletin, include completion of 45 units of unduplicated course work after the bachelor’s degree. Among the department requirements are a grade point average (GPA) of at least 3.0 (B) for the following required courses (or their equivalents):

- PHYSICS 220 Classical Electrodynamics
- PHYSICS 271 Thermodynamics, Kinetic Theory, and Statistical Mechanics II

Plus one of the following courses:
- PHYSICS 230 Quantum Mechanics
- PHYSICS 231 Quantum Mechanics
- PHYSICS 234 Advanced Topics in Quantum Mechanics
- PHYSICS 330 Quantum Field Theory I
- PHYSICS 331 Quantum Field Theory II
- PHYSICS 332 Quantum Field Theory III

**Units:** 14-17

**Units:** 3-4

Up to 6 of these required units may be waived on petition if a thesis is submitted.

### Doctor of Philosophy in Physics

The University’s basic requirements for the Ph.D. are discussed in the "Graduate Degrees (http://exploredegrees.stanford.edu/graduatedegrees) " section of this bulletin.

The minimum department requirements for the Ph.D. degree in Physics consist of completing all courses listed below and at least one course from each of two subject areas outside the student’s primary area of research (among biophysics, condensed matter, quantum optics and atomic physics, astrophysics and gravitation, and nuclear and particle physics). For this requirement students must choose from courses numbered above PHYSICS 234, excluding 270, 271, 290, and 294. For a full list of courses by concentration that satisfy the breadth requirement see the Physics Department (https://physics.stanford.edu) website.

The requirements in the following list may be fulfilled by passing the course at Stanford or passing an equivalent course elsewhere:

**Units:** 3

**Units:** 3-4

**Units:** 1-3

**Units:** 1

**Units:** 3

**Units:** 3

**Units:** 3

**Units:** 3

**Units:** 3

**Units:** 3

**Units:** 3

**Units:** 3

**Units:** 3

**Units:** 3

1 For students who have had a basic introduction to Thermal and Statistical Physics at the advanced undergraduate level. Students who have not had that level of preparation should take PHYSICS 270 prior to taking PHYSICS 271.

A grade point average (GPA) of at least 3.0 (B) is required for courses taken toward the degree.

All Ph.D. candidates must have math proficiency equivalent to the following Stanford MATH courses:

**Units:** 3

**Units:** 3

**Units:** 3

**Units:** 3

Prior to making an application for candidacy, each student is required to pass a comprehensive qualifying examination on undergraduate physics. This closed book exam is given in January following the student's arrival at Stanford. This two-day written examination covers particle mechanics, electricity and magnetism, quantum mechanics, statistical mechanics, thermodynamics, special relativity, and general physics. A thesis proposal must be submitted during the third year. In order to assess the direction and progress toward a thesis, an oral report and evaluation are required during the fourth year. After completion of the dissertation, each student must take the University oral examination (defense of dissertation).

Three quarters of teaching (including a demonstrated ability to teach) are a requirement for obtaining the Ph.D. in Physics.

Students interested in applied physics and biophysics research should also take note of the Ph.D. granted independently by the Department of Applied Physics and by the Biophysics Program. Students interested in astronomy, astrophysics, or space science should also consult the "Astronomy Course Program (http://exploredegrees.stanford.edu/archive/2014-15/schoolofhumanitiesandsciences/astrophysics) " section of this bulletin.

### Ph.D. Minor in Physics

Doctoral students seeking a minor in Physics must take at least six courses from the following list: 210, 211, 216, 220, 230, 231, 234, 270, and 271 among the 20 required units. All prospective minors must obtain
approval of their Physics course program from the Physics Graduate Study Committee at least one year before conferral of the Ph.D.


Chair: Peter M. Michelson

Associate Chair: Mark Kasevich


Associate Professors: Tom Abel, Steven Allen, Chao-Lin Kuo, Hari Manoharan, Xiao-liang Qi, Risa Wechsler

Assistant Professors: Peter Graham, Sean Hartnoll, Jason Hogan, Srinivas Raghu, Monica Schleier-Smith, Leonardo Senateiro, Lauren Tompkins

Professors (Research): Leo Hollberg, Phillip H. Scherrer

Courtesy Professors: Rhiju Das, Benjamin Lev, Craig Levin, Stephen Quake, Richard N. Zare

Lecturers: Chaya Nanavati, Rick Pam

Consulting Professors: Ralph Devoe, Gerald Fisher, Jay Wacker

* Recalled to active duty.

Courses

PHYSICS 15. The Nature of the Universe. 3 Units.
The structure, origin, and evolution of the major components of the Universe: planets, stars, and galaxies. Emphasis is on the formation of the Sun and planets, the evolution of stars, and the structure and content of the Milky Way galaxy. Topics: cosmic enigmas (dark matter, black holes, pulsars, x-ray sources), star birth and death, and the origins of and search for life in the solar system and beyond.

PHYSICS 16. Cosmic Horizons, 3 Units.
The origin and evolution of the universe and its contents: stars, galaxies, quasars. The overall structure of the cosmos and the physical laws that govern matter, space, and time. Topics include the evolution of the cosmos from the origin of the elements and the formation of stars and galaxies, exotic astronomical objects (black holes, quasars, supernovae, and gamma ray bursts), dark matter, inflationary cosmology, and the fate of the cosmos.

PHYSICS 17. Black Holes. 3 Units.
Newton's and Einstein's theories of gravitation and their relationship to the predicted properties of black holes. Their formation and detection, and role in galaxies and high-energy jets. Hawking radiation and aspects of quantum gravity.

PHYSICS 18N. Frontiers in Theoretical Physics and Cosmology. 3 Units.
Preference to freshmen. The course will begin with a description of the current standard models of gravitation, cosmology, and elementary particle physics. We will then focus on frontiers of current understanding including investigations of very early universe cosmology, string theory, and the physics of black holes.

PHYSICS 19. How Things Work: An Introduction to Physics. 3 Units.
Introduction to the principles of physics through familiar objects and phenomena, including airplanes, cameras, computers, engines, refrigerators, lightning, radio, microwave ovens, and fluorescent lights. Estimates of real quantities from simple calculations. Prerequisite: high school algebra and trigonometry.

PHYSICS 21. Mechanics and Heat. 3 Units.
For biology, social science, and premedical students. Introduction to Newtonian mechanics, fluid mechanics, theory of heat. Prerequisite: high school algebra and trigonometry; calculus not required.

PHYSICS 21S. Mechanics and Heat with Laboratory. 4 Units.
For biology, social science, and premedical students. Labs are an integrated part of the summer course. Introduction to Newtonian mechanics, fluid mechanics, theory of heat. nPrerequisite: high school algebra and trigonometry; calculus not required.

PHYSICS 22. Mechanics and Heat Laboratory. 1 Unit.
Guided hands-on exploration of concepts in classical mechanics and thermodynamics with an emphasis on student predictions, observations and explanations. Pre- or corequisite: PHYS 21.

PHYSICS 23. Electricity and Optics. 3 Units.
Electric charges and currents, magnetism, induced currents; wave motion, interference, diffraction, geometrical optics. Prerequisite: PHYSICS 21.

PHYSICS 23S. Electricity and Optics with Lab. 4 Units.
For biology, social science, and premedical students. Labs are an integrated part of the summer courses. Electric charges and currents, magnetism, induced currents; wave motion, interference, diffraction, geometrical optics. nPrerequisite: PHYSICS 21S or 21.

PHYSICS 24. Electricity and Optics Laboratory. 1 Unit.
Guided hands-on exploration of concepts in electricity and magnetism, circuits and optics with an emphasis on student predictions, observations and explanations. Introduction to multimeters and oscilloscopes. Pre- or corequisite: PHYS 23.

PHYSICS 25. Modern Physics. 3 Units.
Introduction to modern physics. Relativity, quantum mechanics, atomic theory, radioactivity, nuclear reactions, nuclear structure, high energy physics, elementary particles, astrophysics, stellar evolution, and the big bang. Prerequisite: PHYSICS 23 or consent of instructor.

PHYSICS 26. Modern Physics Laboratory. 1 Unit.
Guided hands-on and simulation-based exploration of concepts in modern physics, including special relativity, quantum mechanics and nuclear physics with an emphasis on student predictions, observations and explanations. Pre- or corequisite: PHYSICS 25.

PHYSICS 41. Mechanics. 4 Units.
How are the motions of objects in the physical world determined by the laws of physics? In this course, students will learn to describe the motion of objects (kinematics) and then develop an understanding of why motions have the form they do (dynamics). We will emphasize how all the important physical principles in mechanics, such as conservation of momentum and energy for translational and rotational motion, follow from just three “laws” of nature -- Newton’s laws of motion. We will make clear distinctions between the fundamental laws of nature and empirical rules, which are useful approximations for more complex physics. Problems will be drawn from the many examples of mechanics in everyday life. Students will develop skills in verifying that derived results satisfy criteria for correctness, such as dimensional consistency and the expected behavior in limiting cases. Discussions will be based on the language of mathematics -- in particular, vector representations, manipulation of vectors, and calculus. Physical understanding will be fostered by peer interaction and demonstrations in lecture, and discussion sections based on interactive group problem solving. nPrerequisite: High school physics or concurrent enrollment in PHYSICS 41A. MATH 41 or MATH 51 or CME 100 or equivalent. Minimum Corequisite: MATH 42 or equivalent.
PHYSICS 41A. Mechanics Concepts, Calculations, and Context. 1 Unit.
Additional assistance and applications for PHYSICS 41. In-class problems in physics and engineering. Exercises in the concepts and calculations of vectors, translational and rotational velocity and acceleration, equations of motion for particles and rigid bodies, and principles of energy and linear/angular momentum. In-class participation required. Highly recommended for students with limited high school physics or calculus. Co-requisite with PHYSICS 41 for students with no high school physics.

PHYSICS 42. Classical Mechanics Laboratory. 1 Unit.
Hands-on exploration of concepts in classical mechanics: Newton's laws, conservation laws, rotational motion. Introduction to laboratory techniques, experimental equipment and data analysis. Pre- or corequisite: PHYSICS 41.

PHYSICS 43. Electricity and Magnetism. 4 Units.
What is electricity? What is magnetism? And how are they related? How do these phenomena manifest themselves in the physical world? The theory of electricity and magnetism, as codified by Maxwell's equations, underlies much of the observable universe. This course will develop both conceptual and quantitative knowledge of this theory. Topics to be covered include electrostatics; magnetostatics; simple AC and DC circuits involving capacitors, inductors, and resistors; the integral form of Maxwell's equations; and electromagnetic waves. Basic principles will be illustrated in the context of modern technologies. The course will also address broader scientific questions -- How do physical theories evolve? What is the interplay between basic physical theories and their associated technologies? Discussions will be based on the language of mathematics, particularly differential and integral calculus, and vectors. Physical understanding will be fostered by peer interaction and demonstrations in lecture, and discussion sections based on interactive group problem solving. Prerequisite: PHYSICS 41 or equivalent. MATH 42 or MATH 51 or CME 100 or equivalent. Recommended corequisite: MATH 52 or CME 102.

PHYSICS 43A. Electricity and Magnetism: Concepts, Calculations and Context. 1 Unit.
Additional assistance and applications for Physics 43. In-class problems in physics and engineering. Exercises in calculations of electric and magnetic forces and field to reinforce concepts and techniques; Calculations involving inductors, transformers, AC circuits, motors and generators.

PHYSICS 43N. Understanding Electromagnetic Phenomena. 1 Unit.
Preference to freshmen. Expands on the material presented in PHYSICS 43; applications of concepts in electricity and magnetism to everyday phenomena and to topics in current physics research. Corequisite: PHYSICS 43 or advanced placement.

PHYSICS 44. Electricity and Magnetism Lab. 1 Unit.
Hands-on exploration of concepts in electricity and magnetism and circuits. Introduction to multimeters, function generators, oscilloscopes, and graphing techniques. Pre- or corequisite: PHYSICS 43.

PHYSICS 45. Light and Heat. 4 Units.
Reflection and refraction, lenses and lens systems; polarization, interference, and diffraction; temperature, properties of matter and thermodynamics, introduction to kinetic theory of matter. Prerequisites: PHYSICS 41 or equivalent. MATH 21 or MATH 42 or MATH 51 or CME 100 or equivalent.

PHYSICS 45N. Advanced Topics in Light and Heat. 1 Unit.
 Preference to freshmen. Expands on the subject matter presented in PHYSICS 45 to include optics and thermodynamics in everyday life, and applications from modern physics and astrophysics. Corequisite: PHYSICS 45 or advanced placement.

PHYSICS 46. Light and Heat Laboratory. 1 Unit.
Hands-on exploration of concepts in geometrical optics, wave optics and thermodynamics. Pre- or corequisite: PHYSICS 45.

PHYSICS 50. Astronomy Laboratory and Observational Astronomy. 3 Units.
Introduction to observational astronomy emphasizing the use of optical telescopes. Observations of stars, nebulae, and galaxies in laboratory sessions with 16- and 24-inch telescopes at the Stanford Observatory. Meets one evening per week from dusk until well after dark at the Stanford Observatory. No previous physics required. Limited enrollment. Lab.

PHYSICS 59. Frontiers of Physics Research. 1 Unit.
Recommended for prospective Physics and Engineering Physics majors, and anyone with an interest in learning about the big questions and unknowns that physicists tackle in their research at Stanford. Weekly faculty presentations, in some cases followed by tours of experimental laboratories where the research is conducted.

PHYSICS 61. Mechanics and Special Relativity. 4 Units.
(First in a three-part series: PHYSICS 61, PHYSICS 63, PHYSICS 65.) Advanced freshman physics. For students with a strong high school mathematics and physics background contemplating a major in Physics or interested in a rigorous treatment of physics. Special theory of relativity and Newtonian mechanics with multi-variable calculus. Postulates of special relativity, simultaneity, time dilation, length contraction, the Lorentz transformation, causality, and relativistic mechanics. Central forces, contact forces, linear restoring forces. Momentum transport, work, energy, collisions. Angular momentum, torque, moment of inertia in three dimensions. Damped and forced harmonic oscillators. Recommended prerequisites: Mastery of mechanics at the level of AP Physics C and AP Calculus B/C or equivalent. Corequisite: MATH 51.

PHYSICS 62. Classical Mechanics Laboratory. 1 Unit.
Introduction to laboratory techniques, experiment design, data collection and analysis simulations, and correlating observations with theory. Labs emphasize discovery with open-ended questions and hands-on exploration of concepts developed in PHYSICS 61 including Newton's laws, conservation laws, rotational motion. Pre- or corequisite PHYSICS 61.

PHYSICS 63. Electricity, Magnetism, and Waves. 4 Units.

PHYSICS 64. Electricity, Magnetism and Optics Laboratory. 1 Unit.
Introduction to multimeters, breadboards, function generators and oscilloscopes. Emphasis on student-developed design of experimental procedure and data analysis for topics covered in PHYSICS 63: electricity, magnetism, circuits, and optics. Pre- or corequisite: PHYSICS 63.

PHYSICS 65. Quantum and Thermal Physics. 4 Units.
(Third in a three-part series: PHYSICS 61, PHYSICS 63, PHYSICS 65.) Advanced freshman physics. For students with a strong high school mathematics and physics background contemplating a major in Physics or interested in a rigorous treatment of physics. Introduction to quantum mechanics: matter waves, atomic structure, Schrodinger's equation. Thermodynamics and statistical mechanics: entropy and heat, Boltzmann statistics, quantum statistics. Prerequisites: PHYSICS 61 & PHYSICS 63. Pre- or corequisite: MATH 53.
PHYSICS 67. Introduction to Laboratory Physics. 2 Units.
Methods of experimental design, data collection and analysis, statistics, and curve fitting in a laboratory setting. Experiments drawn from electronics, optics, heat, and modern physics. Lecture plus laboratory format.
Required for PHYSICS 60 series Physics and Engineering Physics majors; recommended, in place of PHYSICS 44, for PHYSICS 40 series students who intend to major in Physics or Engineering Physics. Pre- or corequisite: PHYSICS 65 or PHYSICS 43.

PHYSICS 70. Foundations of Modern Physics. 4 Units.
Required for Physics majors who completed the PHYSICS 40 series, or the PHYSICS 60 series prior to 2005-06. Special relativity, the experimental basis of quantum theory, atomic structure, quantization of light, Schrödinger equation, nuclear physics, elementary particles and cosmology. Prerequisites: PHYSICS 41, PHYSICS 43. Pre or corequisite: PHYSICS 45. Recommended: prior or concurrent registration in MATH 53.

PHYSICS 70N. Modern Physics in Your Life. 1 Unit.
How does modern physics intersect with your everyday life? Topics may include the quantum nature of light, atomic physics and an introduction to semiconductor physics, applications to light sources (incandescent, fluorescent, light-emitting diodes, lasers) and light sensors (photodiodes and solar cells), introduction to nuclear physics (e.g., fission, fusion, interaction of radiation with matter). Co- or pre-requisite: PHYSICS 70, PHYSICS 65, or similar high-school physics preparation.

PHYSICS 81N. Science on the Back of the Envelope. 3 Units.
Understanding the complex world around us quantitatively, using order of magnitude estimates and dimensional analysis. Starting from a handful of fundamental constants of Nature, one can estimate complex quantities such as cosmological length and time scales, size of the atom, height of Mount Everest, speed of tsunami, energy density of fuels and climate effects. Through these examples students learn the art of deductive thinking, fundamental principles of science and the beautiful unity of nature.

PHYSICS 83N. Physics in the 21st Century. 3 Units.
Preference to freshmen. Current topics at the frontier of modern physics. Topics include subatomic particles and the standard model, symmetries in nature, extra dimensions of space, string theory, supersymmetry, the big bang theory of the origin of the universe, black holes, dark matter, and dark energy of the universe. Why the sun shines. Cosmology and inflation.

PHYSICS 91SI. Practical Computing for Scientists. 2 Units.
Essential computing skills for researchers in the natural sciences. Helping students transition their computing skills from a classroom to a research environment. Topics include the Unix operating system, the Python programming language, and essential tools for data analysis, simulation, and optimization. More advanced topics as time allows. Prerequisite: CS106A or equivalent.

PHYSICS 100. Introduction to Observational and Laboratory Astronomy. 4 Units.
Designed for undergraduate physics majors but open to all students with a calculus-based physics background and some laboratory experience. Students make and analyze observations using telescopes at the Stanford Student Observatory. Topics include navigating the night sky, the physics of stars and galaxies, telescope instrumentation and operation, quantitative error analysis, and effective scientific communication. Limited enrollment. Prerequisites: prior completion of Physics 40 or PHYSICS 60 series.

PHYSICS 105. Intermediate Physics Laboratory I: Analog Electronics. 4 Units.
Analog electronics including Ohm's law, passive circuits and transistor and op amp circuits, emphasizing practical circuit design skills to prepare undergraduates for laboratory research. Short design project. Minimal use of math and physics, no electronics experience assumed beyond introductory physics. Prerequisite: PHYSICS 43 or PHYSICS 63.

PHYSICS 107. Intermediate Physics Laboratory II: Experimental Techniques and Data Analysis. 4 Units.
Experiments on lasers, Gaussian optics, and atom-light interaction, with emphasis on data and error analysis techniques. Students describe a subset of experiments in scientific paper format. Prerequisites: completion of PHYSICS 40 or PHYSICS 60 series, and PHYSICS 70 and PHYSICS 105. Recommended: PHYSICS 130, prior or concurrent enrollment in PHYSICS 120. WIM.

PHYSICS 108. Advanced Physics Laboratory: Project. 4 Units.
Small student groups plan, design, build, and carry out a single experimental project in low-temperature physics. Prerequisites PHYSICS 105, PHYSICS 107.

PHYSICS 110. Advanced Mechanics. 3-4 Units.
Lagrangian and Hamiltonian mechanics. Principle of least action, Euler-Lagrange equations. Small oscillations and beyond. Symmetries, canonical transformations, Hamilton-Jacobi theory, action-angle variables. Introduction to classical field theory. Selected other topics, including nonlinear dynamical systems, attractors, chaotic motion. Undergraduates register for Physics 110 (4 units). Graduates register for Physics 210 (3 units). (Graduate student enrollees will be required to complete additional assignments in a format determined by the instructor.) Prerequisites: MATH 131P, and PHYS 112 or MATH elective 104 or higher. Recommended prerequisite: PHYS 130.
Same as: PHYSICS 210

PHYSICS 112. Mathematical Methods of Physics. 4 Units.
Theory of complex variables, complex functions, and complex analysis. Fourier series and Fourier transforms. Special functions such as Laguerre, Legendre, and Hermite polynomials, and Bessel functions. The uses of Green's functions. Covers material of MATH 106 and MATH 132 most pertinent to Physics majors. Prerequisites: MATH 50 or 50H series, and MATH 131P or MATH 173.

PHYSICS 113. Computational Physics. 4 Units.
Numerical methods for solving problems in mechanics, electromagnetism, quantum mechanics, and statistical mechanics. Methods include numerical integration; solutions of ordinary and partial differential equations; solutions of the diffusion equation, Laplace's equation and Poisson's equation with relaxation methods; statistical methods including Monte Carlo techniques; matrix methods and eigenvalue problems. Short introduction to MatLab, used for class examples; class projects may be programmed in any language such as C. Prerequisites: MATH 53 and PHYS 120. Previous programming experience not required.

PHYSICS 120. Intermediate Electricity and Magnetism I. 4 Units.
(First in a two-part series: PHYS 120, PHYS 121.) Vector analysis. Electrostatic fields, including boundary-value problems and multipole expansion. Dielectrics, static and variable magnetic fields, magnetic materials. Maxwell's equations. Prerequisites: PHYSICS 43 or PHYS 63; MATH 52 and MATH 53. Pre- or corequisite: MATH 131P or MATH 173. Recommended corequisite: PHYS 112.

PHYSICS 121. Intermediate Electricity and Magnetism II. 4 Units.
(Second in a two-part series: PHYS 120, PHYS 121.) Conservation laws and electromagnetic waves, Poynting's theorem, tensor formulation, potentials and fields. Plane wave problems (free space, conductors and dielectric materials, boundaries). Dipole and quadrupole radiation. Special relativity and transformation between electric and magnetic fields. Prerequisites: PHYS 120 and MATH 131P or MATH 173; Recommended: PHYS 112.
PHYSICS 130. Quantum Mechanics. 4 Units.
The origins of quantum mechanics and wave mechanics. Schrödinger equation and solutions for one-dimensional systems. Commutation relations. Generalized uncertainty principle. Time-energy uncertainty principle. Separation of variables and solutions for three-dimensional systems; application to hydrogen atom. Spherically symmetric potentials and angular momentum eigenstates. Spin angular momentum. Addition of angular momentum. Prerequisites: PHYSICS 65 or PHYSICS 70. Pre- or corequisites: PHYSICS 120 and MATH 131P or MATH 173.

PHYSICS 131. Quantum Mechanics II. 4 Units.
Identical particles; Fermi and Bose statistics. Time-independent perturbation theory. Fine structure, the Zeeman effect and hyperfine splitting in the hydrogen atom. Time-dependent perturbation theory. Variational principle and WKB approximation. Prerequisite: PHYSICS 120, PHYSICS 130, MATH 131P, or MATH 173. Pre- or PHYSICS 121.

PHYSICS 134. Advanced Topics in Quantum Mechanics. 3-4 Units.
Scattering theory, partial wave expansion, Born approximation. Additional topics may include nature of quantum measurement, EPR paradox, Bell's inequality, and topics in quantum information science: path integrals and applications; Berry's phase; structure of multi-electron atoms (Hartree-Fock); relativistic quantum mechanics (Dirac equation). Undergraduates register for PHYSICS 134 (4 units). Graduate students register for PHYSICS 234 (3 units); graduate students required to complete additional assignments in a format determined by the instructor. Prerequisites: PHYSICS 130, PHYSICS 131. Same as: PHYSICS 234

PHYSICS 152. Introduction to Particle Physics I. 3 Units.
Elementary particles and the fundamental forces. Quarks and leptons. The mediators of the electromagnetic, weak and strong interactions. Interaction of particles with matter; particle acceleration, and detection techniques. Symmetries and conservation laws. Bound states. Decay rates. Cross sections. Feynman diagrams. Introduction to Feynman integrals. The Dirac equation. Feynman rules for quantum electrodynamics and for chromodynamics. Undergraduates register for PHYSICS 152. Graduate students register for PHYSICS 252. (Graduate student enrollees will be required to complete additional assignments in a format determined by the instructor.) Prerequisite: PHYSICS 130. Pre- or corequisite: PHYSICS 131. Same as: PHYSICS 252

PHYSICS 160. Introduction to Stellar and Galactic Astrophysics. 3-4 Units.
Observed characteristics of stars and the Milky Way galaxy. Physical processes in stars and matter under extreme conditions. Structure and evolution of stars from birth to death. White dwarfs, planetary nebulae, supernovae; application to hydrogen, helium, and metals, binary stars, x-ray stars, and black holes. Galactic structure, interstellar medium, molecular clouds, HI and HII regions, star formation, and element abundances. Undergraduates register for PHYSICS 160. Graduate students register for PHYSICS 260. (Graduate student enrollees will be required to complete additional assignments in a format determined by the instructor.) Pre or corequisites: PHYSICS 130. Same as Physics 260. Same as: PHYSICS 260

PHYSICS 161. Introduction to Extragalactic Astrophysics and Cosmology. 3 Units.
Big bang theory, cosmic inflation, expansion of space. Composition of the universe. Origin of matter and the elements. The cosmic distance ladder. Observational evidence for dark matter and dark energy. Geometry of space and the standard model of cosmology. Formation of galaxies and large scale structure. Ultimate fate of the universe. Undergraduates register for Physics 161. Graduate register for Physics 261. (Graduate student enrollees will be required to complete additional assignments in a format determined by the instructor). Pre or corequisites: PHYSICS 121. Same as: PHYSICS 261

PHYSICS 170. Thermodynamics, Kinetic Theory, and Statistical Mechanics I. 3-4 Units.
Foundations of statistical mechanics. Thermodynamic variables and basic thermodynamics. Ideal gases (including Maxwell-Boltzmann distribution), Bose and Fermi gases; examples including blackbody radiation, Debye theory of phonons, Sommerfeld theory of electrons in metals, Thermodynamic functions. Undergraduates register for PHYSICS 170 (4 units). Graduates register for Physics 270 (3 units). (Graduates student enrollees will be required to complete additional assignments in a format determined by the instructor.) Recommended prerequisite: PHYSICS 130. Same as: PHYSICS 270

PHYSICS 171. Thermodynamics, Kinetic Theory, and Statistical Mechanics II. 3-4 Units.
Mean-field theory of phase transitions; critical exponents. Ferromagnetism, the Ising model. The renormalization group. Dynamics near equilibrium: Brownian motion, diffusion, Boltzmann equations. Other topics at discretion of instructor. Prerequisite: PHYS 170/270. Undergraduates register for Physics 171 (4 units). Graduate students register for Physics 271 (3 units). (Graduates student enrollees will be required to complete additional assignments in a format determined by the instructor.) Recommended pre- or corequisite: PHYS 130. Same as Physics 271. Same as: PHYSICS 271

PHYSICS 172. Solid State Physics. 3 Units.
Introduction to the properties of solids. Crystal structures and bonding in materials. Momentum-space analysis and diffraction probes. Lattice dynamics, phonon theory and measurements, thermal properties. Electronic structure theory, classical and quantum; free, nearly-free, and tight-binding limits. Electron dynamics and basic transport properties; quantum oscillations. Properties and applications of semiconductors. Reduced-dimensional systems. (Graduate student enrollees will be required to complete additional assignments in a format determined by the instructor.) Undergraduates should register for PHYSICS 172 and graduate students for APPPHYS 272. Prerequisites: PHYSICS 170 and PHYSICS 171, or equivalents. Same as APPPHYS 272. Same as: APPPHYS 272

PHYSICS 190. Independent Research and Study. 1-9 Unit.
Undergraduate research in experimental or theoretical physics under the supervision of a faculty member. Prerequisites: superior work as an undergraduate Physics major and consent of instructor.

PHYSICS 205. Senior Thesis Research. 1-12 Unit.
Long-term experimental or theoretical project and thesis in Physics under supervision of a faculty member. Planning of the thesis project is recommended to begin as early as middle of the junior year. Successful completion of a senior thesis requires a minimum of 3 units for a letter grade completed during the senior year, along with the other formal thesis and physics major requirements. Students doing research for credit prior to senior year should sign up for Physics 190. Prerequisites: superior work as an undergraduate Physics major and approval of the thesis application.

PHYSICS 210. Advanced Mechanics. 3-4 Units.
Lagrangian and Hamiltonian mechanics. Principle of least action, Euler-Lagrange equations. Small oscillations and beyond. Symmetries, canonical transformations, Hamilton-Jacobi theory, action-angle variables. Introduction to classical field theory. Selected other topics, including nonlinear dynamical systems, attractors, chaotic motion. Undergraduates register for Physics 110 (4 units). Graduates register for Physics 210 (3 units). (Graduate student enrollees will be required to complete additional assignments in a format determined by the instructor.) Prerequisites: MATH 131P, and PHYS 112 or MATH elective 104 or higher. Recommended prerequisite: PHYS 130. Same as: PHYSICS 110

PHYSICS 211. Continuum Mechanics. 3 Units.
Elasticity, fluids, turbulence, waves, gas dynamics, shocks, and MHD plasmas. Examples from everyday phenomena, geophysics, and astrophysics.
PHYSICS 216. Back of the Envelope Physics. 3 Units.
Techniques such as scaling and dimensional analysis, useful to make order-of-magnitude estimates of physical effects in different settings. Goals are to promote a synthesis of physics through solving problems, including problems that are not usually thought of as physics. Applications include properties of materials, fluid mechanics, geophysics, astrophysics, and cosmology. Prerequisites: undergraduate mechanics, statistical mechanics, electricity and magnetism, and quantum mechanics.

PHYSICS 220. Classical Electrodynamics. 3 Units.
Special relativity: The principles of relativity, Lorentz transformations, four vectors and tensors, relativistic mechanics and the principle of least action. Lagrangian formulation, charges in electromagnetic fields, gauge invariance, the electromagnetic field tensor, covariant equations of electrodynamics and mechanics, four-current and continuity equation. Noether's theorem and conservation laws, Poynting's theorem, stress-energy tensor. Constant electromagnetic fields: conductors and dielectrics, magnetic media, electric and magnetic forces, and energy. Electromagnetic waves: Plane and monochromatic waves, spectral resolution, polarization, electromagnetic properties of matter, dispersion relations, wave guides and cavities. Prerequisites: PHYSICS 121 and PHYSICS 210, or equivalent; MATH 106 or MATH 116, and MATH 132 or equivalent.

PHYSICS 230. Quantum Mechanics. 3 Units.
Fundamental concepts. Introduction to Hilbert spaces and Dirac's notation. Postulates applied to simple systems, including those with periodic structure. Symmetry operations and gauge transformation. The path integral formulation of quantum statistical mechanics. Problems related to measurement theory. The quantum theory of angular momenta and central potential problems. Prerequisite: PHYSICS 131 or equivalent.

PHYSICS 231. Quantum Mechanics. 3 Units.

PHYSICS 234. Advanced Topics in Quantum Mechanics. 3-4 Units.
Scattering theory, partial wave expansion, Born approximation. Additional topics may include nature of quantum measurement, EPR paradox, Bell's inequality, and topics in quantum information science; path integrals and applications; Berry's phase; structure of multi-electron atoms (Hartree-Fock); relativistic quantum mechanics (Dirac equation). Undergraduates register for PHYSICS 134 (4 units). Graduate students register for PHYSICS 234 (3 units); graduate students required to complete additional assignments in a format determined by the instructor. Prerequisites: PHYSICS 130, PHYSICS 131. Same as: PHYSICS 134

PHYSICS 240. Introduction to the Physics of Energy. 3 Units.

PHYSICS 241. Introduction to Nuclear Energy. 3 Units.

PHYSICS 252. Introduction to Particle Physics I. 3 Units.
Elementary particles and the fundamental forces. Quarks and leptons. The mediators of the electromagnetic, weak and strong interactions. Interaction of particles with matter; particle acceleration, and detection techniques. Symmetries and conservation laws. Bound states. Decay rates. Cross sections. Feynman diagrams. Introduction to Feynman integrals. The Dirac equation. Feynman rules for quantum electrodynamics and for chromodynamics. Undergraduates register for PHYSICS 152. Graduate students register for PHYSICS 252. (Graduates student enrollees will be required to complete additional assignments in a format determined by the instructor.) Prerequisite: PHYSICS 130. Pre- or corequisite: PHYSICS 131. Same as: PHYSICS 152

PHYSICS 260. Introduction to Stellar and Galactic Astrophysics. 3-4 Units.
Observed characteristics of stars and the Milky Way galaxy. Physical processes in stars and matter under extreme conditions. Structure and evolution of stars from birth to death. White dwarfs, planetary nebulae, supernovae, neutron stars, pulsars, binary stars, x-ray stars, and black holes. Galactic structure, interstellar medium, molecular clouds, HI and HII regions, star formation, and element abundances. Undergraduates register for PHYSICS 160. Graduate students register for PHYSICS 260. (Graduate student enrollees will be required to complete additional assignments in a format determined by the instructor.) Pre or corequisites: PHYSICS 130. Same as Physics 260. Same as: PHYSICS 160

PHYSICS 261. Introduction to Extragalactic Astrophysics and Cosmology. 3 Units.
Big bang theory, cosmic inflation, expansion of space. Composition of the universe. Origin of matter and the elements. The cosmic distance ladder. Observational evidence for dark matter and dark energy. Geometry of space and the standard model of cosmology. Formation of galaxies and large scale structure. Ultimate fate of the universe. Undergraduates register for Physics 161. Graduates register for Physics 261. (Graduate student enrollees will be required to complete additional assignments in a format determined by the instructor). Pre or corequisites: PHYSICS 121. Same as PHYSICS 161

PHYSICS 262. Introduction to Gravitation. 3 Units.
Introduction to general relativity. Curvature, energy-momentum tensor, Einstein field equations. Weak field limit of general relativity. Black holes, relativistic stars, gravitational waves, cosmology. Prerequisite: PHYSICS 121 or equivalent including special relativity.

PHYSICS 270. Thermodynamics, Kinetic Theory, and Statistical Mechanics I. 3-4 Units.
Foundations of statistical mechanics. Thermodynamic variables and basic thermodynamics. Ideal gases (including Maxwell-Boltzmann distribution). Bose and Fermi gases; examples including blackbody radiation, Debye theory of phonons, Sommerfeld theory of electrons in metals. Thermodynamic functions. Undergraduates register for PHYSICS 170 (4 units). Graduates register for PHYSICS 270 (3 units). (Graduates student enrollees will be required to complete additional assignments in a format determined by the instructor.) Recommended prerequisite: PHYSICS 130. Same as: PHYSICS 170
PHYSICS 271. Thermodynamics, Kinetic Theory, and Statistical Mechanics II. 3-4 Units.
Mean-field theory of phase transitions; critical exponents. Ferromagnetism, the Ising model. The renormalization group. Dynamics near equilibrium: Brownian motion, diffusion, Boltzmann equations. Other topics at discretion of instructor. Prerequisite: PHYS 170/270. Undergraduates register for PHYS 171 (4 units). Graduate students register for PHYS 271 (3 units). (Graduates student enrollees will be required to complete additional assignments in a format determined by the instructor.) Recommended pre- or corequisite: PHYS 130. Same as Physics 271.

Same as PHYSICS 171

PHYSICS 290. Research Activities at Stanford. 1 Unit.
Required of first-year Physics graduate students; suggested for junior or senior Physics majors for 1 unit. Review of research activities in the department and elsewhere at Stanford at a level suitable for entering graduate students.

PHYSICS 291. Practical Training. 1-3 Unit.
Opportunity for practical training in industrial labs. Arranged by student with the research adviser's approval. A brief summary of activities is required, approved by the research adviser.

PHYSICS 293. Literature of Physics. 1-15 Unit.
Study of the literature of any special topic. Preparation, presentation of reports. If taken under the supervision of a faculty member outside the department, approval of the Physics chair required. Prerequisites: 25 units of college physics, consent of instructor.

PHYSICS 294. Teaching of Physics Seminar. 1 Unit.
Required of all Teaching Assistants prior to the first teaching assignment. Weekly seminar/discussions on interactive techniques for teaching physics. Practicum which includes class observations, grading, and student teaching in current courses.

PHYSICS 295. Learning & Teaching of Science. 3 Units.
This course will provide students with a basic knowledge of the relevant research in cognitive psychology and science education and the ability to apply that knowledge to enhance their ability to learn and teach science, particularly at the undergraduate level. Course will involve readings, discussion, and application of the ideas through creation of learning activities. It is suitable for advanced undergraduates and graduate students with some science background.

Same as: EDUC 280X

PHYSICS 301. Astrophysics Laboratory. 3 Units.
Open to all graduate students with a calculus-based physics background and some laboratory experience. Students make and analyze observations using telescopes at the Stanford Student Observatory. Topics include navigating the night sky, the physics of stars and galaxies, telescope instrumentation and operation, quantitative error analysis, and effective scientific communication. The course also introduces a number of hot topics in astrophysics and cosmology. Limited enrollment.

PHYSICS 312. Basic Plasma Physics. 3 Units.
For the nonspecialist who needs a working knowledge of plasma physics for space science, astrophysics, fusion, or laser applications. Topics: orbit theory, the Boltzmann equation, fluid equations, magneto hydrodynamics (MHD) waves and instabilities, electromagnetic (EM) waves, the Vlasov theory of electrostatic (ES) waves and instabilities including Landau damping and quasilinear theory, the Fokker-Planck equation, and relaxation processes. Advanced topics in resistive instabilities and particle acceleration. Prerequisite: PHYSICS 220, or consent of instructor.

PHYSICS 321. Laser Spectroscopy. 3 Units.

PHYSICS 330. Quantum Field Theory I. 3 Units.

PHYSICS 331. Quantum Field Theory II. 3 Units.

PHYSICS 332. Quantum Field Theory III. 3 Units.

PHYSICS 351. Standard Model of Particle Physics. 3 Units.
Symmetries, group theory, gauge invariance, Lagrangian of the Standard Model, flavor group, flavor-changing neutral currents, CKM quark mixing matrix, GIM mechanism, rare processes, neutrino masses, seesaw mechanism, QCD confinement and chiral symmetry breaking, instantons, strong CP problem, QCD axion. Prerequisite: PHYSICS 330; PHYSICS 331 and PHYSICS 332 recommended.

PHYSICS 361. Advanced Topics in Radiative Processes and Stellar Astrophysics. 3 Units.
Astronomical data on stars, star clusters, interstellar medium, and the Milky Way galaxy. Theory of stellar structure; hydrostatic equilibrium, radiation balance, and energy production. Stellar formation, Jean's mass, and protostars. Evolution of stars to the main sequence and beyond to red giants, white dwarfs, neutron stars, and black holes. Supernovae and compact sources. Structure of the Milky Way: disk and spiral arms; dark matter and the halo mass; central bulge or bar; and black hole. Prerequisite: PHYSICS 221 or equivalent. Recommended: PHYSICS 260, PHYSICS 360.

PHYSICS 362. Advanced Extragalactic Astrophysics and Cosmology. 3 Units.
Observational data on the content and activities of galaxies, the content of the Universe, cosmic microwave background radiation, gravitational lensing, and dark matter. Models of the origin, structure, and evolution of the Universe based on the theory of general relativity. Test of the models and the nature of dark matter and dark energy. Physics of the early Universe, inflation, baryosynthesis, nucleosynthesis, and galaxy formation. Prerequisites: PHYSICS 210, PHYSICS 211, and PHYSICS 260 or PHYSICS 360.
PHYSICS 364. Advanced Gravitation. 3 Units.
Classical and quantum gravity in Anti-de Sitter spacetime (AdS).
History and uses of AdS. Basic classical physics of AdS: metric,
conformal structure, common coordinate systems. Black holes in AdS:
thermodynamics, Hawking-Page transition. Classical fields in AdS: action
of conformal group, singletons. Stability of AdS and positive energy
theorems. Towards the holographic correspondence: geodesics and the UV-
IR relation. AdS from supergravity. Recommended: PHYSICS 330, some
familiarity with general relativity.

PHYSICS 372. Condensed Matter Theory I. 3 Units.
Fermi liquid theory, many-body perturbation theory, response function,
functional integrals, interaction of electrons with impurities. Prerequisite:
APPHYS 273 or equivalent.

PHYSICS 373. Condensed Matter Theory II. 3 Units.
Superfluidity and superconductivity. Quantum magnetism. Prerequisite:
PHYSICS 372.

PHYSICS 450. Conformal Field Theory. 3 Units.
This course will be a systematic introduction to two dimensional conformal
field theory. Topics to be covered include: conformal symmetry; stress
tensor; operator product expansion; Virasoro algebra; unitarity; modular
invariance; c-theorem; conformal bootstrap; Kac-Moody algebra;
supersymmetry.

PHYSICS 451. TOPICS IN STRING THEORY. 3 Units.
The course will cover several topics in modern string theory including
aspects of 2d conformal field theory, mirror symmetry, geometric
transitions and large N dualities, and moonshine. Other topics may
be discussed as time and interests dictate. Prerequisites: No formal
requirements, but a familiarity with quantum field theory at the level of the
330 sequence, and some moderate mathematical maturity, will be useful.

PHYSICS 490. Research. 1-15 Unit.
Open only to Physics graduate students, with consent of instructor. Work is
in experimental or theoretical problems in research, as distinguished from
independent study of a non-research character in 190 and 293.

PHYSICS 801. TGR Project. 0 Units.

PHYSICS 802. TGR Dissertation. 0 Units.