PHYSICS

Courses offered by the Department of Physics are listed under the subject code PHYSICS on the Stanford Bulletin’s ExploreCourses website.

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/astronomy)" 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>Course Code</th>
<th>Course Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHYSICS 15</td>
<td>Stars and Planets in a Habitable Universe</td>
<td>3</td>
</tr>
<tr>
<td>PHYSICS 16</td>
<td>The Origin and Development of the Cosmos</td>
<td>3</td>
</tr>
<tr>
<td>PHYSICS 17</td>
<td>Black Holes and Extreme Astrophysics</td>
<td>3</td>
</tr>
<tr>
<td>PHYSICS 19</td>
<td>How Things Work: An Introduction to Physics (not offered 2016/17)</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>Course Code</th>
<th>Course Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHYSICS 21</td>
<td>Mechanics, Fluids, and Heat</td>
<td>4</td>
</tr>
<tr>
<td>PHYSICS 22</td>
<td>Mechanics, Fluids, and Heat Laboratory</td>
<td>1</td>
</tr>
<tr>
<td>PHYSICS 23</td>
<td>Electricity, Magnetism, and Optics</td>
<td>4</td>
</tr>
<tr>
<td>PHYSICS 24</td>
<td>Electricity, Magnetism, and Optics Laboratory</td>
<td>1</td>
</tr>
<tr>
<td>PHYSICS 25</td>
<td>Modern Physics</td>
<td>4</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:
Graduate Programs in Physics

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). 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). 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). 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).
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 Diagnostic 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.

<table>
<thead>
<tr>
<th>200</th>
<th>300</th>
<th>400</th>
</tr>
</thead>
<tbody>
<tr>
<td>first-year graduate courses</td>
<td>more advanced courses</td>
<td>research, special, or current topics</td>
</tr>
</tbody>
</table>

The second digit indicates the general subject matter:

<table>
<thead>
<tr>
<th>Digit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>laboratory</td>
</tr>
<tr>
<td>10,20,30</td>
<td>general courses</td>
</tr>
<tr>
<td>40</td>
<td>nuclear physics, nuclear energy, energy</td>
</tr>
<tr>
<td>50</td>
<td>elementary particle physics</td>
</tr>
<tr>
<td>60</td>
<td>astrophysics, cosmology, gravitation</td>
</tr>
<tr>
<td>70</td>
<td>condensed matter physics</td>
</tr>
<tr>
<td>80</td>
<td>optics and atomic physics</td>
</tr>
<tr>
<td>90</td>
<td>miscellaneous courses</td>
</tr>
</tbody>
</table>

| PHYSICS 67 | Introduction to Laboratory Physics |

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

- **MATH 51** Linear Algebra and Differential Calculus of Several Variables ³ 
- or **MATH 61CM** Modern Mathematics: Continuous Methods
- **MATH 52** Integral Calculus of Several Variables ³ 
- or **MATH 62CM** Modern Mathematics: Continuous Methods
- **MATH 53** Ordinary Differential Equations with Linear Algebra ³ 
- or **MATH 63CM** Modern Mathematics: Continuous Methods
- **MATH 131P** Partial Differential Equations ³ 
- or **MATH 173** Theory of Partial Differential Equations

Plus one advanced mathematics elective (3-5 units) ³-5

Select one of the following:

Any MATH (101 or higher)

- **PHYSICS 112** Mathematical Methods of Physics 4
- **STATS 116** Theory of Probability 3-5
- EE 261 The Fourier Transform and Its Applications 3

**Intermediate Sequence**

- **PHYSICS 105** Intermediate Physics Laboratory I: Analog Electronics 4
- **PHYSICS 107** Intermediate Physics Laboratory II: Experimental Techniques and Data Analysis 4
- **PHYSICS 112** Mathematical Methods of Physics (recommended) 4
- **PHYSICS 113** Computational Physics (recommended) ² 4
- **PHYSICS 120** Intermediate Electricity and Magnetism I 4
- **PHYSICS 121** Intermediate Electricity and Magnetism II 4

**Advanced Sequence**

- **PHYSICS 108** Advanced Physics Laboratory: Project 4
- **PHYSICS 110** Advanced Mechanics 4
- **PHYSICS 130** Quantum Mechanics I 4
- **PHYSICS 131** Quantum Mechanics II 4
- **PHYSICS 134** Advanced Topics in Quantum Mechanics ² 3-4
- **PHYSICS 170** Thermodynamics, Kinetic Theory, and Statistical Mechanics I 4
- **PHYSICS 171** Thermodynamics, Kinetic Theory, and Statistical Mechanics II 4

**Total Units** 101-107

¹ Those wishing to pursue theoretical physics in graduate school may wish to take a collection of courses in the Department of Mathematics rather than or in addition to PHYSICS 112 Mathematical Methods of Physics.

² These courses are not required. PHYSICS 113 Computational Physics is recommended for students planning to work in technical fields. Both PHYSICS 113 Computational Physics and PHYSICS 134 Advanced Topics in Quantum Mechanics are recommended for students who intend to complete a Ph.D. in Physics.

³ MATH 51H, 52H and/or 53H, offered prior to 2016-17, may be substituted for the MATH 50 and/or 60CM series.

⁴ In years when MATH 173 Theory of Partial Differential Equations is not offered, MATH 220 Partial Differential Equations of Applied Mathematics is a recommended alternative.
Physics majors who wish to prepare for more data-intensive work could consider a minor in Computer Science.

**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 3 units
  - APPPHYS 270: Magnetism and Long Range Order in Solids 3 units
  - MATSCI 195: Waves and Diffraction in Solids 3-4 units

- **Lasers**
  - EE 236A: Modern Optics 3 units
  - EE 236C: Lasers 3 units
  - Lab Methods

- **APPPHYS 207**: Laboratory Electronics 4 units
- **APPPHYS 304**: Lasers Laboratory 4 units

**B. Astrophysics (Bruce Macintosh (bmacintosh@stanford.edu))**

- **PHYSICS 100**: Introduction to Observational Astrophysics 4 units
- **PHYSICS 160**: Introduction to Stellar and Galactic Astrophysics 3 units
- **PHYSICS 161**: Introduction to Cosmology and Extragalactic Astrophysics 3 units

Select one of the following:
- **PHYSICS 211**: Continuum Mechanics 3 units
- **PHYSICS 262**: General Relativity 3 units
- **GS 122**: Planetary Systems: Dynamics and Origins 3-4 units

**PHYSICS 160 and PHYSICS 161** are jointly taught to undergraduates and graduate students (PHYSICS 260 and PHYSICS 261 are for graduate students). Undergraduates must register for 160/161 not 260/261.

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

- **BIOC 202**: Biochemistry Bootcamp 1 unit
- **BIO 141**: Biostatistics 3-5 units
- **BIO 217**: Neuronal Biophysics 4 units
- **BIOE 221**: Physics and Engineering of Radionuclide-based Medical Imaging 3 units
- **BIOE 222**: Instrumentation and Applications for Multi-modality Molecular Imaging of Living Subjects 4 units

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))**

- **GEOPHYS 110**: Introduction to the foundations of contemporary geophysics 3 units
- **GEOPHYS 120**: Ice, Water, Fire 3-5 units

Select one of the following:
- **GEOPHYS 130**: Introductory Seismology 3 units
- **GEOPHYS 150**: Geodynamics: Our Dynamic Earth 3 units
- **GEOPHYS 186**: Tectonophysics 3 units
- **GEOPHYS 190**: Near-Surface Geophysics 3 units

Some classes taught alternate years only. If the class you need or want is not taught in your senior year, contact Prof. Klemperer for alternatives.

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

- **PHYSICS 152**: Introduction to Particle Physics I 3 units
- **PHYSICS 160**: Introduction to Stellar and Galactic Astrophysics 3 units
- **PHYSICS 161**: Introduction to Cosmology and Extragalactic Astrophysics 3 units
- **PHYSICS 262**: General Relativity 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
- **PHYSICS 450**: Advanced Theoretical Physics I: String Theory with Applications to Cosmology and Black Hole Physics 3 units
- **PHYSICS 451**: Advanced Theoretical Physics II: Quantum Information Theory, Complexity, Gravity and Black Holes 3 units
- **PHYSICS 470**: Topics in Modern Condensed Matter Theory I: Topological States of Matter 3 units
- **PHYSICS 471**: Topics in Modern Condensed Matter Theory II: Physics of the Quantum Hall Regime 3 units

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 I and PHYSICS 131 Quantum Mechanics II and PHYSICS 134 Advanced Topics in Quantum Mechanics.
3. Students who took PHYSICS 362 or PHYSICS 364 in previous years may also count these towards fulfillment of this requirement.

**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.

Students who take the PHYSICS 20, 40, or 60 series at Stanford in support of their major may count those units towards the minor.

## Concentration in Physics

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

<table>
<thead>
<tr>
<th>Series</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Series A (19 units)</td>
<td></td>
</tr>
<tr>
<td>PHYSICS 41</td>
<td>Mechanics</td>
</tr>
<tr>
<td>&amp; PHYSICS 42</td>
<td>and Classical Mechanics Laboratory</td>
</tr>
<tr>
<td>PHYSICS 43</td>
<td>Electricity and Magnetism</td>
</tr>
<tr>
<td>&amp; PHYSICS 44</td>
<td>and Electricity and Magnetism Laboratory</td>
</tr>
<tr>
<td>PHYSICS 45</td>
<td>Light and Heat</td>
</tr>
<tr>
<td>&amp; PHYSICS 46</td>
<td>and Light and Heat Laboratory</td>
</tr>
<tr>
<td>PHYSICS 70</td>
<td>Foundations of Modern Physics</td>
</tr>
<tr>
<td>Series B (16 units)</td>
<td></td>
</tr>
<tr>
<td>PHYSICS 61</td>
<td>Mechanics and Special Relativity</td>
</tr>
<tr>
<td>&amp; PHYSICS 62</td>
<td>and Mechanics Laboratory</td>
</tr>
</tbody>
</table>

**Technical**

For students whose majors require the PHYSICS 40 or 60 series:

<table>
<thead>
<tr>
<th>Series</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Series A</td>
<td></td>
</tr>
<tr>
<td>PHYSICS 41</td>
<td>Mechanics</td>
</tr>
<tr>
<td>PHYSICS 43</td>
<td>Electricity and Magnetism</td>
</tr>
<tr>
<td>PHYSICS 45</td>
<td>Light and Heat</td>
</tr>
<tr>
<td>&amp; PHYSICS 46</td>
<td>and Light and Heat Laboratory</td>
</tr>
<tr>
<td>PHYSICS 70</td>
<td>Foundations of Modern Physics</td>
</tr>
<tr>
<td>Series B</td>
<td></td>
</tr>
<tr>
<td>PHYSICS 61</td>
<td>Mechanics and Special Relativity</td>
</tr>
<tr>
<td>PHYSICS 63</td>
<td>Electricity, Magnetism, and Waves</td>
</tr>
<tr>
<td>PHYSICS 65</td>
<td>Quantum and Thermal Physics</td>
</tr>
<tr>
<td>PHYSICS 67</td>
<td>Introduction to Laboratory Physics</td>
</tr>
</tbody>
</table>

And take the following three courses:

<table>
<thead>
<tr>
<th>Series</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHYSICS 100</td>
<td>Introduction to Observational Astrophysics</td>
</tr>
<tr>
<td>PHYSICS 160</td>
<td>Introduction to Stellar and Galactic Astrophysics</td>
</tr>
</tbody>
</table>
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):

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHYSICS 212</td>
<td>Statistical Mechanics</td>
<td>3</td>
</tr>
<tr>
<td>PHYSICS 220</td>
<td>Classical Electrodynamics</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Plus one of the following courses:</td>
<td></td>
</tr>
<tr>
<td>PHYSICS 230</td>
<td>Graduate Quantum Mechanics I</td>
<td>3</td>
</tr>
<tr>
<td>PHYSICS 234</td>
<td>Advanced Topics in Quantum Mechanics</td>
<td>3</td>
</tr>
<tr>
<td>PHYSICS 330</td>
<td>Quantum Field Theory I</td>
<td>3</td>
</tr>
<tr>
<td>PHYSICS 331</td>
<td>Quantum Field Theory II</td>
<td>3</td>
</tr>
<tr>
<td>PHYSICS 332</td>
<td>Quantum Field Theory III</td>
<td>3</td>
</tr>
</tbody>
</table>

Plus two 3 unit graduate level courses in Physics or Applied Physics. 6

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 290 and 294.

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

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHYSICS 212</td>
<td>Statistical Mechanics</td>
<td>3</td>
</tr>
<tr>
<td>PHYSICS 220</td>
<td>Classical Electrodynamics</td>
<td>3</td>
</tr>
<tr>
<td>PHYSICS 290</td>
<td>Research Activities at Stanford</td>
<td>1</td>
</tr>
<tr>
<td>PHYSICS 294</td>
<td>Teaching of Physics Seminar</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Plus one of the following courses:</td>
<td></td>
</tr>
<tr>
<td>PHYSICS 230</td>
<td>Graduate Quantum Mechanics I</td>
<td>3</td>
</tr>
<tr>
<td>PHYSICS 231</td>
<td>Graduate Quantum Mechanics II</td>
<td>3</td>
</tr>
<tr>
<td>PHYSICS 234</td>
<td>Advanced Topics in Quantum Mechanics</td>
<td>3</td>
</tr>
<tr>
<td>PHYSICS 330</td>
<td>Quantum Field Theory I</td>
<td>3</td>
</tr>
<tr>
<td>PHYSICS 331</td>
<td>Quantum Field Theory II</td>
<td>3</td>
</tr>
</tbody>
</table>

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:

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>MATH 106</td>
<td>Functions of a Complex Variable</td>
<td>3</td>
</tr>
<tr>
<td>MATH 113</td>
<td>Linear Algebra and Matrix Theory</td>
<td>3</td>
</tr>
<tr>
<td>MATH 116</td>
<td>Complex Analysis</td>
<td>3</td>
</tr>
<tr>
<td>PHYSICS 112</td>
<td>Mathematical Methods of Physics</td>
<td>4</td>
</tr>
</tbody>
</table>

Prior to making an application for candidacy, each student is required to pass a comprehensive oral qualifying examination. 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/schoolofhumanitiesandsciences/astronomy)" 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, 212, 216, 220, 230, 231, and 234 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 conferment of the Ph.D.


*Chair*: Peter F. Michelson

*Associate Chair*: Shamit Kachru


*Associate Professors*: Sean Hartnoll, Chao-Lin Kuo, Benjamin Lev, Hari Manoharan, Xiao-liang Qi, Leonardo Senatore, Risa Wechsler

*Assistant Professors*: Peter Graham, Jason Hogan, Srinivas Raghu, Monika Schleier-Smith, Lauren Tompkins

*Professors (Research)*: Leo Hollberg, Phillip H. Scherrer
PHYSICS 12N. Black Holes: Fact and Fancy. 3 Units.
Black holes have been observed throughout the universe using radio waves, light, X- and gamma-rays and now with gravitational radiation. They are well-described using Einstein’s theory of relativity and provide dramatic demonstrations of how physicists think about matter, energy, space, and time. They have also stimulated much science fiction. This seminar is intended primarily for non-science freshmen who should learn how some really big ideas were developed, debated, and then demonstrated to be correct. Movies and popular books will be critiqued and used to illustrate basic properties of black holes. Special attention will be paid to understanding what it takes for an interesting idea to become accepted or rejected as scientific fact. There will be visits to Stanford labs where instruments used to observe black holes were conceived, constructed and combined.

PHYSICS 14N. Quantum Information: Visions and Emerging Technologies. 3 Units.
What sets quantum information apart from its classical counterpart is that it can be encoded non-locally, woven into correlations among multiple qubits in a phenomenon known as entanglement. Will discuss paradigms for harnessing entanglement to solve hitherto intractable computational problems or to push the precision of sensors to their fundamental quantum mechanical limits. Will also examine challenges that physicists and engineers are tackling in the laboratory today to enable the quantum technologies of the future.

PHYSICS 15. Stars and Planets in a Habitable Universe. 3 Units.
Is the Earth unique in our galaxy? Students learn how stars and our galaxy have evolved and how this produces planets and the conditions suitable for life. Discussion of the motion of the night sky and how telescopes collect and analyze light. The life-cycle of stars from birth to death, and the end products of that life cycle -- from dense stellar corpses to supernova explosions. Course covers recent discoveries of extrasolar planets -- those orbiting stars beyond our sun -- and the ultimate quest for other Earths. Intended to be accessible to non-science majors, material is explored quantitatively with problem sets using basic algebra and numerical estimates. Sky observing exercise and observational field trips supplement the classroom work.

PHYSICS 16. The Origin and Development of the Cosmos. 3 Units.
How did the present Universe come to be? The last few decades have seen remarkable progress in understanding this age-old question. Course will cover the history of the Universe from its earliest moments to the present day, and the physical laws that govern its evolution. The early Universe including inflation and the creation of matter and the elements. Recent discoveries in our understanding of the makeup of the cosmos, including dark matter and dark energy. Evolution of galaxies, clusters, and quasars, and the Universe as a whole. Implications of dark matter and dark energy for the future evolution of the cosmos. Intended to be accessible to non-science majors, material is explored quantitatively with problem sets using basic algebra and numerical estimates.

PHYSICS 17. Black Holes and Extreme Astrophysics. 3 Units.
Black holes represent an extreme frontier of astrophysics. Course will explore the most fundamental and universal force -- gravity -- and how it controls the fate of astrophysical objects, leading in some cases to black holes. How we discover and determine the properties of black holes and their environment. How black holes and their event horizons are used to guide thinking about mysterious phenomena such as Hawking radiation, wormholes, and quantum entanglement. How black holes generate gravitational waves and powerful jets of particles and radiation. Other extreme objects such as pulsars. Relevant physics, including relativity, is introduced and treated at the algebraic level. No prior physics or calculus is required, although some deep thinking about space, time, and matter is important in working through assigned problems.

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, Fluids, and Heat. 4 Units.
How are the motions of objects and the behavior of fluids and gases determined by the laws of physics? Students learn to describe the motion of objects (kinematics) and understand why objects move as they do (dynamics). Emphasis on how Newton’s three laws of motion are applied to solids, liquids, and gases to describe phenomena as diverse as spinning gymnasts, blood flow, and sound waves. Understanding many-particle systems requires connecting macroscopic properties (e.g., temperature and pressure) to microscopic dynamics (collisions of particles). Laws of thermodynamics provide understanding of real-world phenomena such as energy conversion and performance limits of heat engines. Everyday examples are analyzed using tools of algebra and trigonometry. Problem-solving skills are developed, including verifying that derived results satisfy criteria for correctness, such as dimensional consistency and expected behavior in limiting cases. Physical understanding fostered by peer interaction and demonstrations in lecture, and interactive group problem solving in discussion sections. Prerequisite: high school algebra and trigonometry; calculus not required.

PHYSICS 21S. Mechanics, Fluids, and Heat with Laboratory. 5 Units.
How are the motions of objects and the behavior of fluids and gases determined by the laws of physics? Students learn to describe the motion of objects (kinematics) and understand why objects move as they do (dynamics). Emphasis on how Newton’s three laws of motion are applied to solids, liquids, and gases to describe phenomena as diverse as spinning gymnasts, blood flow, and sound waves. Understanding many-particle systems requires connecting macroscopic properties (e.g., temperature and pressure) to microscopic dynamics (collisions of particles). Laws of thermodynamics provide understanding of real-world phenomena such as energy conversion and performance limits of heat engines. Everyday examples are analyzed using tools of algebra and trigonometry. Problem-solving skills are developed, including verifying that derived results satisfy criteria for correctness, such as dimensional consistency and expected behavior in limiting cases. Physical understanding fostered by peer interaction and demonstrations in lecture, and interactive group problem solving in discussion sections. Labs are an integrated part of the summer course. Prerequisite: high school algebra and trigonometry; calculus not required.

PHYSICS 22. Mechanics, Fluids, and Heat Laboratory. 1 Unit.
Guided hands-on exploration of concepts in classical mechanics, fluids, and thermodynamics with an emphasis on student predictions, observations and explanations. Pre- or corequisite: PHYSICS 21.
PHYSICS 23. Electricity, Magnetism, and Optics. 4 Units.
How are electric and magnetic fields generated by static and moving charges, and what are their applications? How is light related to electromagnetic waves? Students learn to represent and analyze electric and magnetic fields to understand electric circuits, motors, and generators. The wave nature of light is used to explain interference, diffraction, and polarization phenomena. Geometric optics is employed to understand how lenses and mirrors form images. These descriptions are combined to understand the workings and limitations of optical systems such as the eye, corrective vision, cameras, telescopes, and microscopes. Discussions based on the language of algebra and trigonometry. Physical understanding fostered by peer interaction and demonstrations in lecture, and interactive group problem solving in discussion sections. Prerequisite: PHYSICS 21 or PHYSICS 21S.

PHYSICS 23S. Electricity, Magnetism, and Optics with Laboratory. 5 Units.
How are electric and magnetic fields generated by static and moving charges, and what are their applications? How is light related to electromagnetic waves? Students learn to represent and analyze electric and magnetic fields to understand electric circuits, motors, and generators. The wave nature of light is used to explain interference, diffraction, and polarization phenomena. Geometric optics is employed to understand how lenses and mirrors form images. These descriptions are combined to understand the workings and limitations of optical systems such as the eye, corrective vision, cameras, telescopes, and microscopes. Discussions based on the language of algebra and trigonometry. Physical understanding fostered by peer interaction and demonstrations in lecture, and interactive group problem solving in discussion sections. Labs are an integrated part of the summer courses. Prerequisite: PHYSICS 21 or PHYSICS 21S.

PHYSICS 24. Electricity, Magnetism, 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. 4 Units.
How do the discoveries since the dawn of the 20th century impact our understanding of 21st-century physics? This course introduces the foundations of modern physics: Einstein’s theory of special relativity and quantum mechanics. Combining the language of physics with tools from algebra and trigonometry, students gain insights into how the universe works on both the smallest and largest scales. Topics may include atomic, molecular, and laser physics; semiconductors; elementary particles and the fundamental forces; nuclear physics (fission, fusion, and radioactivity); astrophysics and cosmology (the contents and evolution of the universe). Emphasis on applications of modern physics in everyday life, progress made in our understanding of the universe, and open questions that are the subject of active research. Physical understanding fostered by peer interaction and demonstrations in lecture, and interactive group problem solving in discussion sections. Prerequisite: PHYSICS 23 or PHYSICS 23S.

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 motions of objects in the physical world determined by laws of physics? Students learn to describe the motion of objects (kinematics) and then understand why motions have the form they do (dynamics). Emphasis on how 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. Distinction made between fundamental laws of nature and empirical rules that are useful approximations for more complex physics. Problems drawn from examples of mechanics in everyday life. Skills developed in verifying that derived results satisfy criteria for correctness, such as dimensional consistency and expected behavior in limiting cases. Discussions based on language of mathematics, particularly vector representations and operations, and calculus. Physical understanding fostered by peer interaction and demonstrations in lecture, and discussion sections based on interactive group problem solving. Prerequisite: High school physics or concurrent enrollment in PHYSICS 41A. MATH 20 or MATH 41 or MATH 51 or CME 100 or equivalent. Minimum corequisite: MATH 21 or 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 or no high school physics or calculus. Co-requisite: PHYSICS 41.

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? 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. Students develop both conceptual and quantitative knowledge of this theory. Topics include: electrostatics; magnetostatics; simple AC and DC circuits involving capacitors, inductors, and resistors; integral form of Maxwell’s equations; electromagnetic waves. Principles illustrated in the context of modern technologies. Broader scientific questions addressed include: How do physical theories evolve? What is the interplay between basic physical theories and associated technologies? Discussions based on the language of mathematics, particularly differential and integral calculus, and vectors. Physical understanding fostered by peer interaction and demonstrations in lecture, and discussion sections based on interactive group problem solving. Prerequisite: PHYSICS 41 or equivalent. MATH 21 or 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. Highly recommended for students with limited or no high school physics or calculus. Co-requisite: PHYSICS 43.

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, magnetism, and circuits. Introduction to multimeters, function generators, oscilloscopes, and graphing techniques. Pre- or corequisite: PHYSICS 43.

PHYSICS 45. Light and Heat. 4 Units.
What is temperature? How do the elementary processes of mechanics, which are intrinsically reversible, result in phenomena that are clearly irreversible when applied to a very large number of particles, the ultimate example being life? In thermodynamics, students discover that the approach of classical mechanics is not sufficient to deal with the extremely large number of particles present in a macroscopic amount of gas. The paradigm of thermodynamics leads to a deeper understanding of real-world phenomena such as energy conversion and the performance limits of thermal engines. In optics, students see how a geometrical approach allows the design of optical systems based on reflection and refraction, while the wave nature of light leads to interference phenomena. The two approaches come together in understanding the diffraction limit of microscopes and telescopes. Discussions based on the language of mathematics, particularly calculus. Physical understanding fostered by peer interaction and demonstrations in lecture, and discussion sections based on interactive group problem solving. Prerequisite: PHYSICS 41 or equivalent. MATH 21 or MATH 42 or MATH 51 or CME 100 or equivalent.

PHYSICS 45N. Topics in Light and Heat. 1 Unit.
Preference to freshmen. Explores the quantum and classical properties of light from stars, lasers and other sources. Includes modern applications ranging from gravity wave interferometers to x-ray lasers.

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. Observational Astronomy Laboratory. 3 Units.
Introduction to observational astronomy emphasizing the use of optical telescopes. Observations of stars, nebulae, and galaxies in laboratory sessions with telescopes at the Stanford Student Observatory. Meets at the observatory one evening per week from dusk until well after dark, in addition to day-time lectures each week. No previous physics required. Limited enrollment.

PHYSICS 59. Frontiers of Physics Research. 1 Unit.
Recommended for prospective Physics or Engineering Physics majors or 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.

PHYSICS 62. 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.
(Second in a three-part advanced freshman physics series: PHYSICS 61, PHYSICS 63, PHYSICS 65.) This course covers the foundations of electricity and magnetism for students with a strong high school mathematics and physics background, who are contemplating a major in Physics or Engineering Physics, or are interested in a rigorous treatment of physics. Electricity, magnetism, and waves with some description of optics. Electrostatics and Gauss’ law. Electric potential, electric field, conductors, image charges. Electric currents, DC circuits. Moving charges, magnetic field, Ampere’s law. Solenoids, transformers, induction, AC circuits, resonance. Relativistic point of view for moving charges. Displacement current, Maxwell’s equations. Electromagnetic waves, dielectrics. Diffraction, interference, refraction, reflection, polarization. Prerequisite: PHYSICS 61 and MATH 51. Pre- or corequisite: MATH 52.

PHYSICS 64. Electricity, Magnetism and Waves 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.

PHYSICS 70. Foundations of Modern Physics. 4 Units.
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. This course provides an in-depth examination of two of the biggest physics discoveries of the 21st century: that of the Higgs boson and Dark Energy. Through studying these discoveries we will explore the big questions driving modern particle physics, the study of nature’s most fundamental pieces, and cosmology, the study of the evolution and nature of the universe. Questions such as: What is the universe made of? What are the most fundamental particles and how do they interact with each other? What can we learn about the history of the universe and what does it tell us about it’s future? We will learn about the tools scientists use to study these questions such as the Large Hadron Collider and the Hubble Space Telescope. We will also learn to convey these complex topics in engaging and diverse terms to the general public through writing and reading assignments, oral presentations, and multimedia projects. The syllabus includes a tour of SLAC, the site of many major 20th century particle discoveries, and a virtual visit of the control room of the ATLAS experiment at CERN amongst other activities. No prior knowledge of physics is necessary; all voices are welcome to contribute to the discussion about these big ideas. Learning Goals: By the end of the quarter you will be able to explain the major questions that drive particle physics and cosmology to your friends and peers. You will understand how scientists study the impossibly small and impossibly large and be able to convey this knowledge in clear and concise terms.

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 95Q. The Philosophies of Three Great Physicists. 3 Units.
Richard Feynman has famously said, Philosophy of science is about as useful to scientists as ornithology is to birds. A closer look at key moments in the history of physics, however, reveals a different picture. Contrary to the misconception that philosophy has nothing to offer to science in general, and physics in particular, watershed moments in the development of physics were inspired and motivated by deeply held philosophical principles. Similarly, important developments in physics have generated important and difficult philosophical questions. In this sophomore seminar we will explore three significant moments in the development of physics surrounding the works of Newton, Einstein, and Bohr. We will analyze the relationship between the prevailing philosophical views they espoused and the physics they produced. How did Newton come to the view of absolute and fixed space and time? What led Einstein to reject the notion of a fixed space and time and propose a relativistic, and even dynamic space-time? What is Bohr’s influential doctrine of complementary, and why did several generations of physicists believe it to be an adequate philosophical response to quantum mechanics? We will see that the relationship between philosophy and physics is more similar to the relationship between mathematics and physics where progress in one area is often preceded and followed by progress in the second.

PHYSICS 100. Introduction to Observational Astrophysics. 4 Units.
Designed for undergraduate physics majors but open to all students with a calculus-based physics background and some laboratory and coding experience. Students make and analyze observations using the telescopes at the Stanford Student Observatory. Topics covered include navigating the night sky, the physics of stars and galaxies, telescope instrumentation and operation, imaging and spectroscopic techniques, quantitative error analysis, and effective scientific communication. The course concludes with an independent project. Limited enrollment. Prerequisites: prior completion of Physics 40 or 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 pre- or corequisites: PHYSICS 120 and 130, 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). Prerequisites: MATH 131P, and PHYSICS 112 or MATH 131P or MATH elective 104 or higher. Recommended prerequisite: PHYSICS 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, astrophysics, 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 various methods; statistical methods including Monte Carlo techniques; matrix methods and eigenvalue problems. Short introduction to Python, used for class examples; class projects may be programmed in any language such as C, python or Julia. No Prerequisites. Previous programming experience not required.

PHYSICS 120. Intermediate Electricity and Magnetism I. 4 Units.
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. 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 quadruple 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 I. 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 and MATH 131P or MATH 173. MATH 173 can be taken concurrently. Pre- or corequisites: PHYSICS 120.

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 corequisite: 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). Prerequisite: 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 students 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 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 students will be required to complete additional assignments in a format determined by the instructor.) Prerequisite: PHYSICS 121. Same as: PHYSICS 260

PHYSICS 161. Introduction to Cosmology and Extragalactic Astrophysics. 3 Units. What do we know about the physical origins, content, and evolution of the Universe -- and how do we know it? Students learn how cosmological distances and times, and the geometry and expansion of space, are described and measured. Composition of the Universe. Origin of matter and the elements. Observational evidence for dark matter and dark energy. Thermal history of the Universe, from inflation to the present. Emergence of large-scale structure from quantum perturbations in the early Universe. Astrophysical tools used to learn about the Universe. Big open questions in cosmology. Undergraduates register for PHYSICS 161. Graduate students register for PHYSICS 261. (Graduate students will be required to complete additional assignments in a format determined by the instructor.) Prerequisite: PHYSICS 121 or equivalent. Same as: PHYSICS 261

PHYSICS 170. Thermodynamics, Kinetic Theory, and Statistical Mechanics I. 4 Units. Basic probability and statistics for random processes such as random walks. The derivation of laws of thermodynamics from basic postulates; the determination of the relationship between atomic substructure and macroscopic behavior of matter. Temperature; equations of state, heat, internal energy, equipartition; entropy, Gibbs paradox; equilibrium and reversibility; heat engines; applications to various properties of matter; absolute zero and low-temperature phenomena. Distribution functions, fluctuations, the partition function for classical and quantum systems, irreversible processes. Pre- or corequisite: PHYSICS 130.

PHYSICS 171. Thermodynamics, Kinetic Theory, and Statistical Mechanics II. 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: PHYSICS 170. Recommended pre- or corequisite: PHYSICS 130.

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. Undergraduates should register for PHYSICS 172 and graduate students for APPPHYS 272. Prerequisites: PHYSICS 170 and PHYSICS 171, or equivalents. 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 199. The Physics of Energy and Climate Change. 3 Units. Topics include measurements of temperature and sea level changes in the climate record of the Earth, satellite atmospheric spectroscopy, satellite gravity geodesy measurements of changes in water aquifers and glaciers, and ocean changes. The difference between weather fluctuations changes and climate change, climate models and their uncertainties in the context of physical, chemical and biological feedback mechanisms to changes in greenhouse gases and solar insolation will be discussed. Energy efficiency, transmission and distribution of electricity, energy storage, and the physics of harnessing fossil, wind, solar, geothermal, fission and fusion will be covered, along with prospects of future technological developments in energy use and production. Prerequisite: Physics 40 or Physics 60 series.
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). Prerequisites: MATH 131P, and PHYSICS 112 or MATH elective 104 or higher. Recommended prerequisite: PHYSICS 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 212. Statistical Mechanics. 3 Units.

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. Graduate Quantum Mechanics I. 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. Graduate Quantum Mechanics II. 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). Prerequisite: 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. (Graduate students 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 134

PHYSICS 260. Introduction to Stellar and Galactic Astrophysics. 3 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 students will be required to complete additional assignments in a format determined by the instructor.) Prerequisite: PHYSICS 121. Same as: PHYSICS 160
PHYSICS 261. Introduction to Cosmology and Extragalactic Astrophysics. 3 Units.
What do we know about the physical origins, content, and evolution of the Universe – and how do we know it? Students learn how cosmological distances and times, and the geometry and expansion of space, are described and measured. Composition of the Universe. Origin of matter and the elements. Observational evidence for dark matter and dark energy. Thermal history of the Universe, from inflation to the present. Emergence of large-scale structure from quantum perturbations in the early Universe. Astrophysical tools used to learn about the Universe. Big open questions in cosmology. Undergraduates register for Physics 161. Graduates register for Physics 261. (Graduate students will be required to complete additional assignments in a format determined by the instructor.) Prerequisite: PHYSICS 121 or equivalent. Same as: PHYSICS 161

PHYSICS 262. General Relativity. 3 Units.
Einstein's General Theory of Relativity is a basis for modern ideas of fundamental physics, including string theory, as well as for studies of cosmology and astrophysics. The course begins with an overview of special relativity, and the description of gravity as arising from curved space. From Riemannian geometry and the geodesic equations, to curvature, the energy-momentum tensor, and the Einstein field equations. Applications of General Relativity: topics may include experimental tests of General Relativity and the weak-field limit, black holes (Schwarzschild, charged Reissner-Nordstrom, and rotating Kerr black holes), gravitational waves (including detection methods), and an introduction to cosmology (including cosmic microwave background radiation, dark energy, and experimental probes). Prerequisite: PHYSICS 121 or equivalent including special relativity.

PHYSICS 269. Neutrinos in Astrophysics and Cosmology. 3 Units.
Basic neutrino properties. Flavor evolution in vacuum and in matter. Oscillations of atmospheric, reactor and beam neutrinos. Measurements of solar neutrinos; physics of level-crossing and the resolution of the solar neutrino problem. Roles of neutrinos in stellar evolution; bounds from stellar cooling. Neutrinos and stellar collapse; energy transport, collective flavor oscillations, neutrino flavor in turbulent medium. Ultra-high-energy neutrinos. The cosmic neutrino background, its impact on the cosmic microwave background and structure formation; cosmological bounds on the neutrino sector. Prerequisites/corequisites: PHYSICS 121, 131 and 171 or equivalent. PHYS 230-231, 152 and 161 or equivalent are helpful, but not required. May be repeat for credit.

PHYSICS 282. Introduction to Modern Atomic Physics and Quantum Optics. 3 Units.
Introduction to modern atomic physics, including laser cooling and trapping, collisions, ultracold and quantum gases, optical lattices, entanglement, and ion trap quantum gates. Introduction to quantum optical theory of light and atom-photon interactions, including cavity QED, quantum trajectory theory, nonlinear optics, and fundamentals of laser spectroscopy including frequency combs. Prerequisites: PHYSICS 131 or 134 and 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.
Weekly seminar/discussions on interactive techniques for teaching physics. Practicum which includes class observations, grading and student teaching in current courses. Required of all Teaching Assistants prior to first teaching assignment. Mandatory attendance at weekly in-class sessions during first 5 weeks of the quarter; mandatory successful completion of all practicum activities. Enrollment by permission. To get a permission number please complete form: http://web.stanford.edu/dept/physics/academics/TA/PH294app.fb If you have not heard from us by the beginning of class, please come to the first class session.

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 280, ENGR 295

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, magnetohydrodynamics (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 360. Modern Astrophysics. 3 Units.
Basic theory of production of radiation in stars, galaxies and diffuse interstellar and intergalactic media and transfer of radiation throughout the universe. Magnetic fields, turbulence shocks and particle acceleration and transport around magnetospheres of planets to clusters of galaxies. Application to compact objects, pulsars and accretion in binary stars and super-massive black holes, supernova remnants, cosmic rays and active galactic nuclei. Prerequisite: PHYSICS 260 or equivalent.

PHYSICS 361. Cosmology. 3 Units.
A comprehensive exposition of the standard model of cosmology, connecting a fundamental physics description to contemporary and proposed observations. Geometry, kinematics, dynamics, and current contents of the Universe at large. History of the universe as it expanded in size by a factor of a trillion, including nucleosynthesis, recombination, and reionization. Evolution of perturbations that eventually grew to form large scale structure, and the influence of this structure on observations of the microwave background and galaxies. Introduction to modern cosmological probes including techniques to measure the expansion history and the growth of structure. The course will conclude with a focused discussion of cosmic inflation, the nature and origin of matter, and the cosmological constant. Recommended prerequisites: PHYSICS 261 or equivalent. Recommended coreq: PHYSICS 368. Offered in Winter 2016 and alternate years thereafter.

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, baryogenesis, nucleosynthesis, and galaxy formation. Prerequisites: PHYSICS 210, PHYSICS 211, and PHYSICS 260 or PHYSICS 360.

PHYSICS 364. Advanced Gravitation. 3 Units.

PHYSICS 366. Special Topics in Astrophysics: Statistical Methods. 2 Units.
Existing and emerging statistical techniques and their application to astronomical surveys and cosmological data analysis. Topics covered will include statistical frameworks (Bayesian inference and frequentist statistics), numerical methods including Markov Chain Monte Carlo, and machine learning applied to classification and regression. Hands-on activities based on open-source software in python.

PHYSICS 367. Special Topics in Astrophysics: Experimental Methods in Particle Astrophysics and Cosmology. 2 Units.
Experimental methods in particle physics, particle astrophysics and cosmology. The course will cover detector fundamentals including the passage of radiation through matter, signal production and collection in detector media, and front-end electronics, with a focus on the fundamental limits of technology. The course will include case studies of specific experiments chosen to illustrate a range of experimental techniques, what the underlying physics questions are and how they are probed with the instrumentation. A typical case study will include instrumentation papers that describe the detector design and a physics results paper that elucidates how the measurement follows from the detector capabilities. Students will make an oral presentation on an experiment, covering both the design of the experiment, and a science result that exploits the apparatus.

PHYSICS 368. Computational Cosmology and Astrophysics. 2 Units.
Create virtual Universes and understand our own using your computer. Techniques for studying the dynamics of dark matter and gas as it assembles over cosmic time to form the structure in the Universe. The use of modern computer codes on supercomputers to combine modeling of gravitation, gas dynamics, radiation processes, magnetohydrodynamics, and other relevant physical processes to make detailed predictions about the evolution of the Universe. Practical exercises to explore how cosmic microwave background observations are sensitive to cosmological parameters, how key numerical algorithms work, how different cosmological observations can be combined to constrain what the Universe is made of and how it changed over time. Additional current topics in computational cosmology depending on student interest. Hands-on activities based on open-source software in C++ and Python. Pre- or corequisites: PHYSICS 361. Recommended prerequisite: PHYSICS 366.

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: APPPHYS 273 or equivalent.

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

PHYSICS 450. Advanced Theoretical Physics I: String Theory with Applications to Cosmology and Black Hole Physics. 3 Units.
String theory provides a strong candidate for quantum gravity as well as contributing insights into many areas of physics. The class will start by evaluating the need for an extension of general relativity and quantum field theory, and assess the circumstances under which it becomes relevant (or ‘dangerously irrelevant’ in the renormalization group sense). We will develop the basic tools for perturbative calculations and study their implications at short and long distances and in nontrivial spacetime geometries and topologies. The course will survey non-perturbative objects, dualities, compactification, and the structure of cosmological backgrounds of string theory, discussing their implications for early universe models and for the problem of upgrading holographic duality to cosmology.

PHYSICS 451. Advanced Theoretical Physics II: Quantum Information Theory, Complexity, Gravity and Black Holes. 3 Units.
This course will cover the developing intersection between quantum information theory and the quantum theory of gravity. We will focus on the central roles of entanglement and computational complexity in black hole physics. Prerequisites: Basic knowledge of quantum mechanics, quantum field theory, and general relativity.
PHYSICS 470. Topics in Modern Condensed Matter Theory I: Topological States of Matter. 3 Units.
A brief introduction to integer quantum Hall effect. Su-Schrieffer-Heeger model and one-dimensional topological insulators. Topological band theory of time-reversal invariant topological insulators. Various approaches of determining the topological invariant from the bulk and the boundary. An overview of key experiments. Topological superconductivity. Topological response theory. A brief summary of more recent developments on interacting topological insulators/symmetry protected topological states. Prerequisite: PHYSICS 172/APPHYS 272 or equivalent; knowledge on second quantization; knowledge on path integral. May be repeat for credit.

PHYSICS 471. Topics in Modern Condensed Matter Theory II: Physics of the Quantum Hall Regime. 3 Units.
Integer quantum Hall effect, Fractional quantum Hall effect, Laughlin’s theory, Hierarchy states, Effective theories, topological order in the fractional quantum Hall effect, physics of the half-filled Landau level, quantum Hall plateau transitions. May be repeat for credit.

PHYSICS 490. Research. 1-18 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 491. Symmetry and Quantum Information. 2 Units.
This course gives an introduction to quantum information theory through the study of symmetries. We start with Bell’s and Tsirelson’s inequalities, which bound the strength of classical and quantum correlations, and discuss their relation to algebraic symmetries. Next, we exploit permutation symmetry to quantify the monogamy of entanglement and explain how to securely distribute a secret key. Lastly, we study quantum information in the limit of many copies and discuss a powerful technique for constructing universal quantum protocols, based on the Schur-Weyl duality between the unitary and symmetric groups. Applications include quantum data compression, state estimation, and entanglement distillation. Prerequisite: PHYSICS 230 or equivalent. All required group and representation theory will be introduced. This course runs for the first five weeks of the quarter.

PHYSICS 801. TGR Project. 0 Units.

PHYSICS 802. TGR Dissertation. 0 Units.