Physics

Courses offered by the Department of Physics are listed under the subject code PHYSICS on the Stanford Bulletin's ExploreCourses web site (http://explorecourses.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/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:

		Units
PHYSICS 15	Stars and Planets in a Habitable Universe	3
PHYSICS 16	The Origin and Development of the Cosmos	3
PHYSICS 17	Black Holes and Extreme Astrophysics	3
PHYSICS 19		

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

		Units
PHYSICS 21	Mechanics Fluids and Heat	4
PHYSICS 22	Mechanics, Fluids, and Heat Laboratory	1
PHYSICS 23	Electricity, Magnetism, and Optics	4
PHYSICS 24	Electricity, Magnetism and Optics Laboratory	1
PHYSICS 25	Modern Physics	4
PHYSICS 26	Modern Physics Laboratory	1

The 40 series (below) is for students majoring in engineering, chemistry, earth sciences, mathematics, or physics:

		Units
PHYSICS 41	Mechanics	4
PHYSICS 42	Classical Mechanics Laboratory	1
PHYSICS 43	Electricity and Magnetism	4
PHYSICS 44	Electricity and Magnetism Lab	1
PHYSICS 45	Light and Heat	4
PHYSICS 46	Light and Heat Laboratory	1

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:

		Units
PHYSICS 61	Mechanics and Special Relativity	4
PHYSICS 62	Mechanics Laboratory	1
PHYSICS 63	Electricity, Magnetism, and Waves	4
PHYSICS 64	Electricity, Magnetism and Waves Laboratory	1
PHYSICS 65	Quantum and Thermal Physics	4
PHYSICS 67	Introduction to Laboratory Physics	2

Physics Placement Diagnostic

Students who are planning to take either of the calculus-based sequences (PHYSICS 40 or 60 sequence) are advised to take the Physics Placement Diagnostic (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-diagnostic. Students who do not plan to take the 40 or 60 sequence do *not* need to take the Placement Diagnostic.

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 15, 2015 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 Nanocharacterization 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 (FGST) and the Large Synoptic Survey Telescope (LSST). KIPAC members also participate fully in the Cryogenic Dark Matter Search (CDMS), the Solar Dynamics Observatory (SDO), the EXO-200 double beta decay experiment, the Dark Energy Survey (DES), the NuSTAR and Astro-H X-ray satellites, 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/centerslaboratoriesandinstitutes/#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:

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

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.

		Units
Introductory Sequence		19-20
Complete either the 40 Series or the 60 Series		
40 Series (19-20 units):		
PHYSICS 41	Mechanics	
PHYSICS 42	Classical Mechanics Laboratory	
PHYSICS 43	Electricity and Magnetism	
PHYSICS 44	Electricity and Magnetism Lab	
or PHYSICS 67	Introduction to Laboratory Physics	
PHYSICS 45	Light and Heat	
PHYSICS 46	Light and Heat Laboratory	
PHYSICS 70	Foundations of Modern Physics	
60 Series (16 units):		
PHYSICS 61	Mechanics and Special Relativity	
PHYSICS 62	Mechanics Laboratory	
PHYSICS 63	Electricity, Magnetism, and Waves	
PHYSICS 64	Electricity, Magnetism and Waves 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 Astrophysics	
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 Cosmology and Extragalactic Astrophysics	
PHYSICS 172	Solid State Physics	
PHYSICS 211	Continuum Mechanics	
PHYSICS 212	Statistical Mechanics	
PHYSICS 216	Back of the Envelope Physics	
PHYSICS 220	Classical Electrodynamics	
PHYSICS 230	Graduate Quantum Mechanics I	
PHYSICS 231	Graduate Quantum Mechanics II	
PHYSICS 262	General Relativity	
Required Math Courses (21-23 units)		
MATH 51	Linear Algebra and Differential Calculus of Several Variables	5
or MATH 51H	Honors Multivariable Mathematics	
MATH 52	Integral Calculus of Several Variables	5
or MATH 52H	Honors Multivariable Mathematics	
MATH 53	Ordinary Differential Equations with Linear Algebra	5
or MATH 53H	Honors Multivariable Mathematics	
MATH 131P	Partial Differential Equations I	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	
STATS 116	Theory of Probability	
EE 261	The Fourier Transform and Its Applications	
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) [1]	
PHYSICS 113	Computational Physics (recommended) [2]	
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]	
PHYSICS 170	Thermodynamics, Kinetic Theory, and Statistical Mechanics I	4

PHYSICS 171	Thermodynamics, Kinetic Theory, and Statistical Mechanics II	4
Total Units		**80-83**

[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.

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))

		Units
Solid State		
PHYSICS 172	Solid State Physics	3
APPPHYS 270	Magnetism and Long Range Order in Solids	3
MATSCI 195	Waves and Diffraction in Solids	3-4
Lasers		
EE 236A	Modern Optics	3
EE 236C	Lasers	3
Lab Methods		
APPPHYS 207	Laboratory Electronics	4
APPPHYS 304	Lasers Laboratory	4

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

		Units
PHYSICS 100	Introduction to Observational Astrophysics	4
PHYSICS 160	Introduction to Stellar and Galactic Astrophysics	3
PHYSICS 161	Introduction to Cosmology and Extragalactic Astrophysics	3
Select one of the following:		3-4
PHYSICS 211	Continuum Mechanics	
PHYSICS 262	General Relativity	
PHYSICS 312	Basic Plasma Physics (not offered 2015-16)	
GS 122	Planetary Systems: Dynamics and Origins	3-4

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

		Units
BIOC 202	Biochemistry Bootcamp	1
BIOPHYS 228	Computational Structural Biology	3
BIO 141	Biostatistics	3-5
BIO 217	Neuronal Biophysics (not offered 2015-16)	4
BIOE 221	Physics and Engineering of Radionuclide Imaging	3
BIOE 222	Instrumentation and Applications for Multi-modality Molecular Imaging of Living Subjects	4

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:

		Units
GEOPHYS 110	Earth on the Edge: Introduction to Geophysics	3
GEOPHYS 120	Ice, Water, Fire	3-5
Select one of the following:		
GEOPHYS 130	Introductory Seismology	
GEOPHYS 186	Tectonophysics	
GEOPHYS 190	Near-Surface Geophysics	

Physics majors matriculating prior to 2010-11 who wish to complete a concentration in Geophysics should consult Prof. Klemperer.

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

		Units
PHYSICS 152	Introduction to Particle Physics I	3
PHYSICS 160	Introduction to Stellar and Galactic Astrophysics	3
PHYSICS 161	Introduction to Cosmology and Extragalactic Astrophysics	3
PHYSICS 262	General Relativity	3
PHYSICS 330	Quantum Field Theory I	3
PHYSICS 331	Quantum Field Theory II	3
PHYSICS 332	Quantum Field Theory III	3
PHYSICS 351	Standard Model of Particle Physics	3

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, 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.
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. 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:

		Units
Select one of the following Series:		16-19
Series A (19 units)		
PHYSICS 41 & PHYSICS 42	Mechanics and Classical Mechanics Laboratory	
PHYSICS 43 & PHYSICS 44	Electricity and Magnetism and Electricity and Magnetism Lab [1]	
PHYSICS 45 & PHYSICS 46	Light and Heat and Light and Heat Laboratory	
PHYSICS 70	Foundations of Modern Physics	
Series B (16 units)		
PHYSICS 61 & PHYSICS 62	Mechanics and Special Relativity and Mechanics Laboratory	
PHYSICS 63 & PHYSICS 64	Electricity, Magnetism, and Waves and Electricity, Magnetism and Waves Laboratory	
PHYSICS 65 & PHYSICS 67	Quantum and Thermal Physics and Introduction to Laboratory Physics	
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, 212, 216, 220, 230, 231, or 262.		9-12
Total Units		**25-31**

[1] PHYSICS 67 Introduction to Laboratory Physics may be substituted for PHYSICS 44 Electricity and Magnetism Lab.

Minor in Physics with Concentration in Astronomy

Students wishing to pursue advanced work in astrophysical sciences should major in Physics (p. 3) and concentrate in astrophysics. However, students outside of Physics with a general interest in astronomy may organize their studies by completing one of the following Physics minor concentration programs.

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

An undergraduate Physics minor with a concentration in Astronomy requires the following courses:

Non-Technical

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

		Units
PHYSICS 21	Mechanics Fluids and Heat	4
PHYSICS 23	Electricity, Magnetism, and Optics	4
PHYSICS 25 & PHYSICS 26	Modern Physics and Modern Physics Laboratory	4
PHYSICS 50 or PHYSICS 100	Observational Astronomy Laboratory / Introduction to Observational Astrophysics	3-4
Select two of the following:		6
PHYSICS 15	Stars and Planets in a Habitable Universe	
PHYSICS 16	The Origin and Development of the Cosmos	
PHYSICS 17	Black Holes and Extreme Astrophysics	
Total Units		**21-22**

Technical

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

		Units
Select one of the following Series:		14-17
Series A		
PHYSICS 41	Mechanics	
PHYSICS 43	Electricity and Magnetism	

PHYSICS 45 & PHYSICS 46	Light and Heat and 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 Astrophysics	4
PHYSICS 160	Introduction to Stellar and Galactic Astrophysics	3
PHYSICS 161	Introduction to Cosmology and Extragalactic Astrophysics	3
Total Units		**24-27**

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):

		Units
PHYSICS 212	Statistical Mechanics	3
PHYSICS 220	Classical Electrodynamics	3
Plus one of the following courses:		
PHYSICS 230	Graduate Quantum Mechanics I	3
PHYSICS 231	Graduate Quantum Mechanics II	3
PHYSICS 234	Advanced Topics in Quantum Mechanics	3
PHYSICS 330	Quantum Field Theory I	3
PHYSICS 331	Quantum Field Theory II	3
PHYSICS 332	Quantum Field Theory III	3
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:

		Units
PHYSICS 212	Statistical Mechanics	3
PHYSICS 220	Classical Electrodynamics	3
PHYSICS 290	Research Activities at Stanford	1
PHYSICS 294	Teaching of Physics Seminar	1
Plus one of the following courses:		
PHYSICS 230	Graduate Quantum Mechanics I	3
PHYSICS 231	Graduate Quantum Mechanics II	3
PHYSICS 234	Advanced Topics in Quantum Mechanics	3
PHYSICS 330	Quantum Field Theory I	3
PHYSICS 331	Quantum Field Theory II	3
PHYSICS 332	Quantum Field Theory III	3

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
MATH 106	Functions of a Complex Variable	3
MATH 113	Linear Algebra and Matrix Theory	3
MATH 116	Complex Analysis	3
MATH 132	Partial Differential Equations II	3

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 conferral of the Ph.D.

Emeriti: (Professors) Alexander L. Fetter, William A. Little, Douglas D. Osheroff, David M. Ritson, H. Alan Schwettman, Robert V. Wagoner, John Dirk Walecka, Stanley G. Wojcicki, Mason R. Yearian; (Professors, Research) John A. Lipa, Todd I. Smith, John P. Turneaure; (Professors, Courtesy) Peter A. Sturrock (Applied Physics), Richard Taylor (SLAC National Accelerator Laboratory)

Chair: Peter M. Michelson

Associate Chair: Mark Kasevich

Professors: Roger Blandford, Phil Bucksbaum, Patricia Burchat, Blas Cabrera, Steven Chu, Sarah Church, Persis Drell, Savas G. Dimopoulos, Sebastian Doniach, David Goldhaber-Gordon, Giorgio Gratta, Patrick Hayden, Kent Irwin, Shamit Kachru, Steven Kahn, Renata E. Kallosh, Aharon Kapitulnik, Mark Kasevich, Steven A. Kivelson, Robert B. Laughlin, Andrei D. Linde, Bruce Macintosh, Kathryn Moler, Peter F. Michelson, Vahe Petrosian, Roger W. Romani, Zhi-Xun Shen, Stephen

Shenker, Eva Silverstein, Leonard Susskind, Carl Wieman, Shoucheng Zhang

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 Senatore, Lauren Tompkins

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

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

Lecturers: Chaya Nanavati, Rick Pam

Consulting Professors: Ralph Devoe, Gerald Fisher

Courses

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 observatory 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 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 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 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 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 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. 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.
(First in a three-part advanced freshman physics series: PHYSICS 61, PHYSICS 63, PHYSICS 65.) This course covers Einstein's special theory of relativity and Newtonian mechanics at a level appropriate 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. 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. Uses the language of vectors and multivariable calculus. Recommended prerequisites: Mastery of mechanics at the level of AP Physics C and AP Calculus BC or equivalent. Corequisite: MATH 51.

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.
(Third in a three-part advanced freshman physics series: PHYSICS 61, PHYSICS 63, PHYSICS 65.) This course introduces the foundations of quantum and statistical mechanics 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. Quantum mechanics: atoms, electrons, nuclei. Quantization of light, Planck's constant. Photoelectric effect, Compton and Bragg scattering. Bohr model, atomic spectra. Matter waves, wave packets, interference. Fourier analysis and transforms, Heisenberg uncertainty relationships. Schrouml;dinger equation, eigenfunctions and eigenvalues. Particle-in-a-box, simple harmonic oscillator, barrier penetration, tunneling, WKB and approximate solutions. Time-dependent and multi-dimensional solution concepts. Coulomb potential and hydrogen atom structure. Thermodynamics and statistical mechanics: ideal gas, equipartition, heat capacity. Probability, counting states, entropy, equilibrium, chemical potential. Laws of thermodynamics. Cycles, heat engines, free energy. Partition function, Boltzmann statistics, Maxwell speed distribution, ideal gas in a box, Einstein model. Quantum statistical mechanics: classical vs. quantum distribution functions, fermions vs. bosons. 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 or Engineering Physics majors who completed the PHYSICS 40 series. Introduction to special relativity: reference frames, Michelson-Morley experiment. Postulates of relativity, simultaneity, time dilation. Length contraction, the Lorentz transformation, causality. Doppler effect. Relativistic mechanics and mass, energy, momentum relations. Introduction to quantum physics: atoms, electrons, nuclei. Quantization of light, Planck constant. Photoelectric effect, Compton and Bragg scattering. Bohr model, atomic spectra. Matter waves, wave packets, interference. Fourier analysis and transforms, Heisenberg uncertainty relationships. Schrouml;dinger equation, eigenfunctions and eigenvalues. Particle-in-a-box, simple harmonic oscillator, barrier penetration, tunneling, WKB and approximate solutions. Time-dependent and multi-dimensional solution concepts. Coulomb potential and hydrogen atom structure. Prerequisites: PHYSICS 41, PHYSICS 43. Pre or corequisite: PHYSICS 45. Recommended: prior or concurrent registration in MATH 53.

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 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 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, 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.
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. Schrouml;dinger 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. 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 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 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.
Principles, ensembles, statistical equilibrium. Thermodynamic functions, ideal and near-ideal gases. Fluctuations. Mean-field description of phase-transitions and associated critical exponents. One-dimensional Ising model and other exact solutions. Renormalization and scaling relations. Prerequisites: PHYSICS 131, 171, or equivalents.

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.
Basis for higher level courses on atomic solid state and particle physics. Problems related to measurement theory and introduction to quantum computing. Approximation methods for time-independent and time-dependent perturbations. Semiclassical and quantum theory of radiation, second quantization of radiation and matter fields. Systems of identical particles and many electron atoms and molecules. Prerequisite: PHYSICS 230.

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.
Energy as a consumable. Forms and interconvertability. World Joule budget. Equivalents in rivers, oil pipelines and nuclear weapons. Quantum mechanics of fire, batteries and fuel cells. Hydrocarbon and hydrogen synthesis. Fundamental limits to mechanical, electrical and magnetic strengths of materials. Flywheels, capacitors and high pressure tanks. Principles of AC and DC power transmission. Impossibility of pure electricity storage. Surge and peaking. Solar constant. Photovoltaic and thermal solar conversion. Physical limits on agriculture.

PHYSICS 241. Introduction to Nuclear Energy. 3 Units.
Radioactivity. Elementary nuclear processes. Energetics of fission and fusion. Cross-sections and resonances. Fissionable and fertile isotopes. Neutron budgets. Light water, heavy water and graphite reactors. World nuclear energy production. World reserves of uranium and thorium. Plutonium, reprocessing and proliferation. Half lives of fission decay products and actinides made by neutron capture. Nuclear waste. Three Mile Island and Chernobyl. Molten sodium breeders. Generation-IV reactors. Inertial confinement and magnetic fusion. Laser compression. Fast neutron production and fission-fusion hybrids. Prerequisities: Strong undergraduate background in elementary chemistry and physics. PHYSICS 240 and PHYSICS 252 recommended but not required. Interested undergraduates encouraged to enroll, with permission of instructor.

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 152

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 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 280

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.
Theoretical concepts and experimental techniques. Absorption, dispersion, Kramers-Kronig relations, line-shapes. Classical and laser linear spectroscopy. Semiclassical theory of laser atom interaction: time-dependent perturbation theory, density matrix, optical Bloch equations, coherent pulse propagation, multiphoton transitions. High-resolution nonlinear laser spectroscopy: saturation spectroscopy, polarization spectroscopy, two-photon and multiphoton spectroscopy, optical Ramsey spectroscopy. Phase conjugation. Four-wave mixing, harmonic generation. Coherent Raman spectroscopy, quantum beats, ultra-sensitive detection. Prerequisite: PHYSICS 230. Recommended: PHYSICS 231.

PHYSICS 330. Quantum Field Theory I. 3 Units.
Lorentz Invariance. S-Matrix. Quantization of scalar and Dirac fields. Feynman diagrams. Quantum electrodynamics. Elementary electrodynamic processes: Compton scattering; e+e- annihilation. Loop diagrams. Prerequisites: PHYSICS 130, PHYSICS 131, or equivalents AND a basic knowledge of Group Theory.

PHYSICS 331. Quantum Field Theory II. 3 Units.
Functional integral methods. Local gauge invariance and Yang-Mills fields. Asymptotic freedom. Spontaneous symmetry breaking and the Higgs mechanism. Unified models of weak and electromagnetic interactions. Prerequisite: PHYSICS 330.

PHYSICS 332. Quantum Field Theory III. 3 Units.
Theory of renormalization. The renormalization group and applications to the theory of phase transitions. Renormalization of Yang-Mills theories. Applications of the renormalization group of quantum chromodynamics. Perturbation theory anomalies. Applications to particle phenomenology. Prerequisite: PHYSICS 331.

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 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 grow 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. 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, 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 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. Recommended prerequisites: PHYSICS 260 and 261, or equivalent. Familiarity with Python coding and basic statistics at level of STATS 116. This course runs for the first five weeks of the quarter.

PHYSICS 367. Special Topics in Astrophysics: High-Energy Astrophysics. 2 Units.
Basic theory of radiative processes, particle acceleration and propagation, compact objects, accretion, and shock fronts, with application to pulsars, X-ray binaries, supernova remnants, cosmic rays, active galactic nuclei, and clusters of galaxies. Prerequisite: PHYSICS 260 or equivalent. This course runs for the first five weeks of the quarter.

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. Quantum Chaos and Quantum Gravity. 3 Units.
Course reviews aspects of classical and quantum chaos; discussions of recent connections of these topics to the physics of black holes and scattering experiments in AdS/CFT; and estimates of a bound on the rate at which chaos can appear in diagnostic correlation functions.

PHYSICS 451. Topics in Modern Condensed Matter Theory. 3 Units.
This course will cover various aspects of modern condensed matter physics with emphasis on statistical field theories. Possible topics include: renormalization group and critical phenomena, quantum phase transitions, disordered systems, quantum Hall systems.

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.
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PHYSICS 802. TGR Dissertation. 0 Units.
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