SCHOOL OF HUMANITIES AND SCIENCES

PHYSICS

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

Chair: Patricia Burchat

Professors: Roger Blandford, Phil Bucksbaum, Patricia Burchat, Blas Cabrera, Savas G. Dimopoulos, Sebastian Doniach, Giorgio Gratta, Shamit Kachru**, Steven Kahn, Renata E. Kallosh, Aharon Kapitulnik, Mark Kasevich, Steven A. Kivelson, Robert B. Laughlin, Andrei D. Linde, Peter F. Michelson, Douglas D. Osheroff, Vahé Petrosian, Roger W. Romani, Zhi-Xun Shen, Stephen Shenker, Eva Silverstein**, Leonard Susskind, Stanley G. Wojcicki, Shoucheng Zhang

Associate Professors: Tom Abel, Steven Allen, Sarah Church, David Goldhaber-Gordon, Kathryn Moler

Assistant Professors: Stefan Funk, Chao-Lin Kuo, Hari Manoharan, Risa Wechsler

Professors (Research): John A. Lipa, Phillip H. Scherrer

Courtesy Professors: Rhiju Das, Richard N. Zare

Lecturer: Rick Pam

Consulting Professors: Ralph Devoe, Gerald Fisher, Barbara Jones, Greg Madejski, Alan Title

Visiting Professors: Francois LeDiberder

* Recalled to active duty.

** On leave

Department Offices: 382 Via Pueblo Mall

Mail Code: 94305-4060

Phone: (650) 723-4344

Web Site: http://stanford.edu/dept/physics

Courses offered by the Department of Physics are listed under the subject code PHYSICS on the *Stanford Bulletin's* ExploreCourses web site.

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, 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 Office 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. Until recently, the PEP-II asymmetric-energy electron-positron storage ring was used to study CP violation in the B meson system. The Stanford Synchrotron Radiation Laboratory (SSRL) uses intense x-ray beams produced with another smaller storage ring on the SLAC site. Construction of the world's first x-ray free electron laser, called the Linac Coherent Light Source (LCLS), was completed in 2009.

The Ginzton Laboratory, HEPL, GLAM, SLAC, and SSRL are listed in the "Academic Programs and Centers, Independent Research Laboratories, Centers, and Institutes" 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 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, including the Fermi Gamma-Ray Space Telescope (FGST, formally known as GLAST), the Large Synoptic Survey Telescope (LSST), the Joint Dark Energy Mission (JDEM) and the Dark Energy Survey (DES). KIPAC members are also involved in several microwave background experiments, new x-ray telescopes, TeV gamma ray astronomy, the Cryogenic Dark Matter Search (CDMS) and the EXO-200 double beta decay experiments. Stanford is a member of the Hobby-Eberly Telescope Consortium, operating an innovative 9.2 meter-equivalent telescope at the McDonald Observatory in Texas. The CDMS (cryogenic dark matter search) experiment is operated in an underground laboratory on the Stanford campus and in the Soudan mine in Minnesota. Stanford is also the center of activities for the very large double-beta decay experiment that is about to start taking data at a deep underground site in New Mexico. The Experiment, called EXO-200, will measure the mass of the neutrino with a sensitivity close to 02.eV. Many research opportunities are available for students in the growing fields of particle astrophysics and cosmology.

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

The Physics Library, a center for the reading and study of physics and astronomy at all levels, includes print and electronic access to current subscriptions and back sets of important journals together with textbooks, dissertations, scholarly monographs, and the collected works of the most eminent physicists.

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 Course Program" section of this bulletin.

Three introductory series of courses include labs in which undergraduates carry out individual experiments. The Intermediate 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 honors program and/or the summer research program.

Graduate students find opportunities for research in the fields of astrophysics, particle astrophysics, cosmology, experimental particle physics, theoretical particle physics, 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, 2009, for the following Autumn Quarter.

Graduate students may normally enter the department only at the beginning of Autumn Quarter.

PHYSICS COURSE CATALOG NUMBERING SYSTEM

There are four series of beginning courses. One course from the teen series (15, 16, 17, 19) is recommended for the humanities or social science student who wishes to become familiar with the methodology and content of modern physics. The 20 series (21, 22, 23, 24, 25, 26) is recommended for general students and for students preparing for medicine or biology. The 40 series (41, 43, 44, 45, 46) is for students of engineering, chemistry, earth sciences, mathematics, or physics. The advanced freshman series (61, 63, 64, 65, 67) is for students who have had strong preparation in physics and calculus in high school. Students who have had appropriate background and wish to major in physics should take this introductory series.

The 20, 40, and 60 series consist of demonstration lectures on the fundamental principles of physics, problem work on application of these principles to actual cases, and lab experiments correlated with the lectures. Their objectives are not only to give information on particular subjects, but also to provide training in the use of the scientific method. The primary difference between the series of courses is that topics are discussed more thoroughly and treated with greater mathematical rigor in the 40 and 60 series.

Courses beyond 99 are numbered in accordance with a three-digit code. The first digit indicates the approximate level of the course:

100	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:

00	laboratory
10,20,30	general courses
50	elementary particle physics
60	astrophysics, cosmology, gravitation
70	condensed matter physics
80	optics and atomic physics
90	miscellaneous courses

UNDERGRADUATE MISSION STATEMENT FOR PHYSICS

The mission of the Physics Program is to provide students with a foundation in both classical and modern physics. Introductory physics courses include a laboratory component. Advanced laboratory courses develop experimental skills and include the design and execution of experiments. Students are also encouraged to participate in independent research projects. The program prepares students for careers in industry, government, teaching, engineering and medicine, as well as graduate programs in physics.

UNDERGRADUATE PROGRAMS IN PHYSICS

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 meet the needs mainly of the third group, but also of some students majoring in other branches of science and in 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 is non-calculus-based, and is intended primarily for those who are majoring in biology. Such students with AP Physics credit, particularly those who are considering research careers, may wish to consider taking the PHYSICS 20 or 40 series, rather than using AP placement. These introductory series provide a depth and emphasis on problem solving that is of significant value in biological research, which today involves considerable physics-based technology.

For those intending to major in engineering or the physical sciences, or simply wishing 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 mechanics in Winter Quarter, electricity and magnetism in Spring Quarter, and light and heat in Autumn Quarter. While it is recommended that most students begin the sequence with mechanics (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 Advanced Placement C exam) may start the sequence with PHYSICS 45 in Autumn Quarter. Effective academic year 2009/2010, all courses for the 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.

BACHELOR OF SCIENCE IN PHYSICS

A calculus-based entry-level series is required, either PHYSICS 61, 63, 64, 65, 67, or 41, 43, 44, 45, 46 (or preferably 67 rather than 44). Students who take the PHYSICS 40 series take PHYSICS 70, which covers the foundations of modern physics. This material was incorporated into the PHYSICS 60 series beginning in 2005-06. Students taking the PHYSICS 60 series in 2005-06 or after do not take PHYSICS 70; instead, they must take one advanced Physics elective (100-level or higher). In addition, the following more advanced courses are required: PHYSICS 105, 107 (WIM), 108, 110, 120, 121, 130, 131, 170, and 171; MATH 51, 52, 53, 131; one additional Mathematics course numbered 101 or higher, or PHYSICS 112. MATH 51H, 52H, and 53H may substitute for MATH 51, 52, and 53. It is strongly recommended that students intending to complete a Ph.D. in Physics also take PHYSICS 113, 134, and one or more of the following, depending upon their interests: PHYSICS 152A,B, 160, 161, 172, 204 and EE 268. PHYSICS 113 is designed to be taken in parallel with 110. The department advises the study of some computer science such as CS 106A/CS106X. Mathematics and Physics courses taken to satisfy the department's major requirements cannot be taken on a credit/no credit basis. Prospective Physics majors are also advised to take PHYSICS 59, Current Research Topics, in their freshman or sophomore year. Effective academic year 2009-10, courses applied to the 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.

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. 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 http://registrar.stanford.edu/students/academics/adv_place.htm.

Undergraduates are offered help with physics problems in the Physics Tutoring Center, which is staffed Monday through Friday.

REQUIRED COURSES FOR MAJORS

For sample schedules illustrating how to complete the Physics major, see http://physics.stanford.edu/academics/undergrad.html.

INTRODUCTORY SEQUENCE

Students must complete either the 40 or 60 series as follows:

40 Series:	*Qtr. and Units*	
PHYSICS 41. Mechanics	W	4
PHYSICS 43. Electricity and Magnetism	S	4
PHYSICS 44. Electricity and Magnetism Lab	S	1
PHYSICS 45. Light and Heat	A	4
PHYSICS 46. Light and Heat Lab	A	1
PHYSICS 67. Introduction to Laboratory Physics (recommended for physics majors in place of 44)	S	2
PHYSICS 70. Foundations of Modern Physics	A	4

60 Series: Subject and Catalog Number	*Qtr. and Units*	
PHYSICS 61. Mechanics and Special Relativity	A	4
PHYSICS 63. Electricity, Magnetism and Waves	W	4
PHYSICS 64. Electromagnetism Lab	W	1
PHYSICS 65. Thermodynamics and Foundations of Modern Physics	S	4
PHYSICS 67. Introduction to Laboratory Physics	S	2
and		
MATH 51, 52, 53. Linear Algebra, Multivariable Calculus, and Ordinary Differential Equations	A,W,S	15
PHYSICS 59. Current Research Topics (recommended)*	A	1

INTERMEDIATE SEQUENCE

PHYSICS 105. Intermediate Laboratory I: Analog Electronics	A	3
PHYSICS 107. Intermediate Laboratory II: Experimental Techniques and Data Analysis (WIM)	W	4
PHYSICS 108. Intermediate Laboratory III: Project	W or S	3
PHYSICS 110. Intermediate Mechanics	S	4
PHYSICS 112. Math Methods of Physics (recommended)**	W	4
PHYSICS 113. Computational Physics (recommended)*	S	4
PHYSICS 120,121. Intermediate Electricity and Magnetism	W,S	8
and MATH 131. Partial Differential Equations	A,W	3

ADVANCED SEQUENCE

PHYSICS 130,131. Quantum Mechanics	A,W	8
PHYSICS 134. Advanced Topics in Quantum Mechanics*	S	4
PHYSICS 170,171. Statistical Mechanics	A,W	8

and one advanced Mathematics elective (100 level or higher) or PHYSICS 112

One advanced Physics elective (100 level or higher): required only for students who are not required to take PHYSICS 70

* These courses are not required; Physics 113 is recommended for students planning to work in technical fields; Both Physics 113 and Physics 134 are recommended for students who intend to complete a Ph.D. in Physics.

** Those wishing to do physics theory in graduate school may wish to take a collection of courses in the Department of Mathematics rather than or in addition to PHYSICS 112.

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.

A. APPLIED PHYSICS (HARI MANOHARAN)

At least four, one quarter courses chosen from the following courses, or three courses plus an honors thesis:

Solid State:

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

Biophysics:

APPPHYS 192. Introductory Biophysics

Lasers:

EE 231. Introduction to Lasers
EE 232. Laser Dynamics
EE 268. Introduction to Modern Optics

Lab Methods:

APPPHYS 207, 208. Laboratory Electronics, Analog and Digital
APPPHYS 304. Lasers Laboratory

B. ASTROPHYSICS (ROGER ROMANI, SARAH CHURCH)

Requirements:

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

Plus one elective from below or an honors thesis:

PHYSICS 211. Continuum Mechanics
PHYSICS 260. Introduction to Astrophysics and Cosmology
PHYSICS 262. Introduction to Gravitation
PHYSICS 312. Basic Plasma Physics; prerequisites are PHYSICS 210 and 220

C. BIOPHYSICS (SEB DONIACH)

At least four, one quarter courses chosen from the following courses, or three courses plus an honors thesis:

APPPHYS 136. Biology by the Numbers
APPPHYS 192/292. Introductory Biophysics
BIOC 202. Metabolic Biochemistry
BIOPHYS 228. Computational Structure Biology
BIO 141. Biostatistics
BIO 132/232. Advanced Imaging Lab In Biophysics
BIO 135/HUMBIO 182. Biological Clocks
BIO 211. Biophysics of Sensory Transduction
BIO 217. Neuronal Biophysics
CS 273. Algorithms for Structure and Motion In Biology

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

D. GEOPHYSICS (SIMON KLEMPERER, GEOPHYSICS)

At least four, one quarter courses chosen from the following courses, or three courses plus an honors thesis:

EE 140. Introduction to Remote Sensing
GEOPHYS 112. Exploring Geosciences with MATLAB
GEOPHYS 150. General Geophysics and Physics of the Earth
GEOPHYS 170. Global Tectonics
GEOPHYS 180. Geophysical Inverse Problems
GEOPHYS 190. Introduction to Geophysical Field Methods
GEOPHYS 222. Reflection Seismology
GEOPHYS 262. Rock Physics
GEOPHYS 288A. Crustal Deformation

E. THEORETICAL PHYSICS (ANDREI LINDE)

At least four, one quarter courses chosen from the following courses, or three courses plus an honors thesis:

PHYSICS 152A,B. Introduction to Particle Physics
PHYSICS 204. Seminar in Theoretical Physics
PHYSICS 212. Statistical Mechanics
PHYSICS 232. Quantum Mechanics
PHYSICS 260. Introduction to Astrophysics and Cosmology
PHYSICS 262. Introduction to Gravitation
PHYSICS 330,331,332. Quantum Field Theory
PHYSICS 351. Standard Model of Particle Physics and Beyond
PHYSICS 352. Neutrino Physics
PHYSICS 362. Advanced Extragalactic Astrophysics and Cosmology
PHYSICS 364. Advanced Gravitation

Notes to students taking this concentration:

1. No more than one of the courses should be taken for CR/NC.
2. Students should discuss the choice of courses with members of the Institute for Theoretical Physics and/or their major adviser.

3. Students may attend 330 after taking 130, 131 and 134. Prior study of special topics in quantum mechanics (232) may be helpful.

INDIVIDUALLY DESIGNED MAJOR PROGRAM IN TEACHING PHYSICAL SCIENCE

This major, a joint effort of the Department of Physics and the Stanford Teacher Education Program (STEP), is designed for students to prepare themselves as high school teachers of physics and general science. Students complete 45-47 units of Physics and related Mathematics courses, 40-43 units of course work in other sciences such as the life sciences, chemistry, and geosciences, and in general issues of science, and 9-15 units of concentration and depth courses. Total program units: 94-105. Students interested in this program should consult Professor Patricia Burchat (burchat@stanford.edu, 725-5771), and Professor Rachel Lotan, Director of the Stanford Teacher Education Program—Secondary in the School of Education (rlotan@stanford.edu).

CORE PHYSICS COURSES:

Mechanics:	*Units*
PHYSICS 41. Mechanics	
or PHYSICS 61. Mechanics and Special Relativity	4
Heat:	
PHYSICS 45. Light and Heat	
PHYSICS 46. Light and Heat Lab	
or	
PHYSICS 65. Thermodynamics and Foundations of Modern Physics	
PHYSICS 67. Introduction to Laboratory Physics	5-6
Electricity and Magnetism:	
PHYSICS 43. Electricity and Magnetism	
PHYSICS 67. Introduction to Laboratory Physics	
or	
PHYSICS 63. Electricity, Magnetism, and Waves	
PHYSICS 64. Electricity and Magnetism Lab	
and	
PHYSICS 105. Analog Electronics (Lab)	8-9
Wave Motion:	
PHYSICS 107 Intermediate Physics Laboratory II: Experimental Techniques and Data Analysis (WIM)	4
Modern Physics (for students who take 40 series):	
PHYSICS 70. Foundations of Modern Physics	4
Applications:	
PHYSICS 59. Current Research Topics	1
Mathematics (Physics departmental requirement):	
MATH 51,52,53. Linear Algebra, Multivariable Calculus, and Ordinary Differential Equations	
and a course in Statistics (choose one):	
STATS 110. Statistical Methods in Engineering and the Physical Sciences	
STATS 116. Theory of Probability	
STATS 141. Biostatistics	
STATS 166. Computational Biology	
STATS 191. Introduction to Applied Statistics	20
Total	46-48

ADDITIONAL SCIENCE BREADTH COURSES

Life Sciences:	
BIO 41. Genetics, Biochemistry, and Molecular Biology	
BIO 42. Cell Biology and Animal Physiology	
BIO 43. Plant Biology, Evolution and Ecology	
or	
HUMBIO 2A,B, 3A,B, 4A,B	15
Chemistry:	
CHEM 31A and B, or 31X. Chemical Principles	
CHEM 33. Structure and Reactivity	8
Geosciences:	
EARTHSYS 10. Introduction to Earth Systems	
PHYSICS 15. The Nature of the Universe	
or PHYSICS 16. Cosmic Horizon	
or PHYSICS 17. Black Holes	8
General Issues of Science:	
STS 101. Science, Technology, and Contemporary Society	
EDUC 180. Directed Reading in History of Science	
ENGR 103. Public Speaking and Presentation Development	9-12

CONCENTRATION AND DEPTH COURSES

3 courses (100 level or above) in a single area of concentration	9-15
Total units for general science	49-58
Total units for the Physical Science program	94-105

This individually designed major program in Physical Science includes all the elements of a Program of Subject Matter Preparation for Secondary Teachers of Physics and General Science that has been approved by the California Commission on Teacher Credentialing (CCTC). Students who complete the program are exempt from taking the CSET examination in Physics and General Science for admission to the Stanford Teacher Education Program (STEP) or any other accredited secondary teacher education program in California. Full details of the CCTC-approved program may be found at http://ed.stanford.edu/suse/programs-degrees/program-coterminal-step.html. Note: the Stanford individually designed major program in Physical Science requires course work beyond the CCTC-approved program, specifically 9-15 units of depth courses in a field of concentration: Physics, Astrophysics, Biology, Chemistry, Earth Sciences, Human Biology, or Computational Mathematics. See the adviser in the Physics department or the School of Education for more details.

HONORS PROGRAM

The department offers a program leading to the degree of Bachelor of Science in Physics with honors as follows:

1. Students must submit an Honors Program Proposal form to the undergraduate program coordinator once they find a physics project, either theoretical or experimental, in consultation with individual faculty members. Proposal forms are available from the Physics undergraduate office and must be submitted by November 1 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. The work done in the honors program may not be used as a substitute for regular required courses.
3. A written report and a presentation of the work at its completion are required for honors. By mid-May, the honors candidate is required to present the project at the department's honors presentations. This event is publicized and open to the general public. The expectation is that the student's adviser, second reader, and all other honors candidates attend.
4. The decision as to whether a given independent study project does or does not merit award of honors is made jointly by the student's honors adviser and the second reader for the written thesis. This decision is based on the quality of the student's honors work and other work in physics.

MINORS

A minor is offered in either Physics or Astronomy. Students who take the 20 or 40 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 series level by enrollment at another accredited university, or through advanced placement credits, may count credits towards 21/22 and 23/24, or 41 and 43/44, respectively. 25/26, or 45/46 for a technical minor, must be taken at Stanford even if similar material has been covered elsewhere. With the 21/22/23/24 or 41/43/44 exception noted above, 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. 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.

MINOR IN PHYSICS

An undergraduate minor in Physics requires a minimum of 27 units with the following course work:

Non-Technical—For students whose majors do not require the PHYSICS 40 or 60 series:

Subject and Catalog Number	*Units*
PHYSICS 21, 22, 23, 24, 25, and 26	12
Any combination of Physics courses totaling 15 units or greater	15
Total	27

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

	Units
PHYSICS 41, 43/44, 45/46 and PHYSICS 70	18
or	
PHYSICS 61, 63/64, 65/67	15
at least three PHYSICS courses numbered 100 or above	9-12
Total	27-30

MINOR IN ASTRONOMY

Students wishing to pursue advanced work in astrophysical sciences should major in physics 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 minor programs.

An undergraduate minor in astronomy requires the following courses:

Non-Technical—For students whose majors do not require the PHYSICS 40 series:

	Units
PHYSICS 21, 23, 25/26	10
PHYSICS 50 or 100 (Observatory Lab)	3-4
Choose two courses from the following:	
PHYSICS 15, 16, 17	6
Total	19-20 (9-10 in addition to the 20 series)

Technical—For students whose majors require the PHYSICS 40 series:

	Units
PHYSICS 41, 43, 45/46	13
PHYSICS 70	4
PHYSICS 100 (Observatory Lab)	4
Choose two courses from the following:	
PHYSICS 160,* 161,* EE 106*	6
Total	27 (14 in addition to the 40 series)

* With approval of the minor adviser and the chair of the Astronomy Course Program, 3 units of PHYSICS 169, Independent Study in Astrophysics, may be substituted for one course of astronomy (e.g., 160, 161, EE 106). This independent study can either be constituted as a directed reading program or participation in a research project. Students are also strongly encouraged to take the electricity and magnetism/optics lab of the appropriate Physics series (24, 44) for 1 additional unit.

GRADUATE PROGRAMS

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.

TEACHING CREDENTIALS

For information on teaching credentials, consult the "School of Education" section of this bulletin or visit http://susestep.stanford.edu. Also see the earlier section on the Individually Designed Major program in Teaching Physical Science.

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" 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 courses 210 or 211, 212, 220, 221, 230, 231, or their equivalents. Up to 6 of these required units may be waived on petition if a thesis is submitted.

DOCTOR OF PHILOSOPHY

The University's basic requirements for the Ph.D. are discussed in the "Graduate Degrees" section of this bulletin. The minimum department requirements for the Ph.D. degree in Physics consist of completing all courses listed below, plus 290 and 294 and at least one quarter from each of two subject areas (among biophysics, condensed matter, quantum optics and atomic physics, astrophysics and gravitation, and nuclear and particle physics) chosen from courses with numbers above 232, except 290 and 294. The requirements in the following list may be fulfilled by passing the course at Stanford or passing an equivalent course elsewhere: 210 or 211, 212, 220, 221, 230, 231. 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: 106, 113, 114, 116, 131, 132.

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

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

Students interested in applied physics and biophysics research should also take note of the Ph.D. granted independently by the Department of Applied Physics and by the Biophysics Program. Students interested in astronomy, astrophysics, or space science should also consult the "Astronomy Course Program" section of this bulletin.

PH.D. MINOR IN PHYSICS

Minors in Physics must take at least six courses numbered 210 to 232 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 award of the Ph.D.

PHYSICS (PHYSICS)

UNDERGRADUATE COURSES IN PHYSICS

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

3 units, Aut (Madejski, G), Sum (Staff)

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

3 units, Win (Romani, R)

PHYSICS 17. Black Holes
Newton's and Einstein's theories of gravitation and their relationship to the predicted properties of black holes. Their formation and detection, and role in galaxies and high-energy jets. Hawking radiation and aspects of quantum gravity. GER: DB-NatSci
3 units, Spr (Abel, T)

PHYSICS 18N. Revolution in Concepts of the Cosmos
(F,Sem) Stanford Introductory Seminar. Preference to freshmen. The evolution of concepts of the cosmos and its origin, from the Copernican heliocentric model to the current view based on Hubble's discovery of expansion of the Universe. Recent cosmological observations and the relevance of laboratory experiments in particle physics. One night of observations at the Stanford Observatory. GER: DB-NatSci
3 units, Win (Roodman, A)

PHYSICS 19. How Things Work: An Introduction to Physics
The principles of physics through familiar objects and phenomena, including airplanes, engines, refrigerators, lightning, radio, TV, microwave ovens, and fluorescent lights. Estimates of real quantities from simple calculations. Prerequisite: high school algebra and trigonometry. GER: DB-NatSci
3 units, Aut (Manoharan, H)

PHYSICS 21. Mechanics and Heat
For biology, social science, and premedical students. Introduction to Newtonian mechanics, fluid mechanics, theory of heat. Prerequisite: high school algebra and trigonometry; calculus not required. GER: DB-NatSci
3 units, Aut (Susskind, L)

PHYSICS 21S. Mechanics and Heat w/ laboratory
Equivalent to 21 and 22. GER: DB-NatSci
4 units, Sum (Fisher, G)

PHYSICS 22. Mechanics and Heat Laboratory
Pre- or corequisite: 21.
1 unit, Aut (Susskind, L)

PHYSICS 23. Electricity and Optics
Electric charges and currents, magnetism, induced currents; wave motion, interference, diffraction, geometrical optics. Prerequisite: 21. GER: DB-NatSci
3 units, Win (Wojcicki, S)

PHYSICS 24. Electricity and Optics Laboratory
Focus is on electrodynamics circuits. Pre- or corequisite: 23.
1 unit, Win (Wojcicki, S)

PHYSICS 25. Modern Physics
Introduction to modern physics. Relativity, quantum mechanics, atomic theory, radioactivity, nuclear reactions, nuclear structure, high energy physics, elementary particles, astrophysics, stellar evolution, and the big bang. Prerequisite: 23 or consent of instructor. GER: DB-NatSci
3 units, Spr (Linde, A)

PHYSICS 25S. Modern Physics with Laboratory
Equivalent to 25 and 26. GER: DB-NatSci
4 units, Sum (Fisher, G)

PHYSICS 26. Modern Physics Laboratory
Pre- or corequisite: 25.
1 unit, Spr (Linde, A)

PHYSICS 28. Mechanics, Heat, and Electricity
For biology, social science, and premedical students. The sequence 28 and 29 fulfills, in ten weeks, the one-year college physics requirement with lab of most medical schools. Topics: Newtonian mechanics, fluid mechanics, theory of heat, electric charges, and currents. Calculus is used as a language and developed as needed. Prerequisite: high school algebra and trigonometry. GER: DB-NatSci
6 units, Sum (Fisher, G)

PHYSICS 29. Electricity and Magnetism, Optics, Modern Physics
Magnetism, induced currents; wave motion, optics; relativity, quantum mechanics, atomic theory, radioactivity, nuclear structure and reactions, elementary particles, astrophysics, and cosmology. Prerequisite: 28. GER: DB-NatSci
6 units, Sum (Fisher, G)

PHYSICS 41. Mechanics
Vectors, particle kinematics and dynamics, work, energy, momentum, angular momentum; conservation laws; rigid bodies; mechanical oscillations and waves. Discussions based on use of calculus. Corequisite: MATH 19 or 41, or consent of instructor. GER: DB-NatSci
4 units, Win (Church, S)

PHYSICS 41N. Mechanics: Insights, Applications, and Advances
(F,Sem) Stanford Introductory Seminar. Preference to freshman. Additional topics for students in PHYSICS 41 such as tidal forces, gyroscopic effects, fractal dimensions, and chaos. Corequisite: 41 or advanced placement.
1 unit, Win (Abel, T)

PHYSICS 43. Electricity and Magnetism
Electrostatics, Coulomb's law, electric fields and fluxes, electric potential, properties of conductors, Gauss's law, capacitors and resistors, DC circuits; magnetic forces and fields, Biot-Savart law, Faraday's law, Ampere's law, inductors, transformers, AC circuits, motors and generators, electric power, Galilean transformation of electric and magnetic fields, Maxwell's equations; limited coverage of electromagnetic fields and special relativity. Prerequisites: 41 or equivialent, and MATH 19 or 41. Corequisite: MATH 20 or 42, or consent of instructor. GER: DB-NatSci
4 units, Spr (Michelson, P)

PHYSICS 43N. Understanding Electromagnetic Phenomena
(F,Sem) Stanford Introductory Seminar. Preference to freshmen. Expands on the material presented in 43; applications of concepts in electricity and magnetism to everyday phenomena and to topics in current physics research. Corequisite: 43 or advanced placement.
1 unit, Spr (Laughlin, R)

PHYSICS 44. Electricity and Magnetism Lab
Pre- or corequisite: 43.
1 unit, Spr (Michelson, P)

PHYSICS 45. Light and Heat
Reflection and refraction, lenses and lens systems; polarization, interference, and diffraction; temperature, properties of matter and thermodynamics, introduction to kinetic theory of matter. Prerequisites: 41 or equivalent, and MATH 19 or 41, or consent of instructor. GER: DB-NatSci
4 units, Aut (Osheroff, D), Sum (Staff)

PHYSICS 45N. Advanced Topics in Light and Heat
(F,Sem) Stanford Introductory Seminar. Preference to freshmen. Expands on the subject matter presented in 45 to include optics and thermodynamics in everyday life, and applications from modern physics and astrophysics. Corequisite: 45 or advanced placement.
1 unit, Aut (Romani, R)

PHYSICS 46. Light and Heat Laboratory
Pre- or corequisite: 45.
1 unit, Aut (Osheroff, D), Sum (Staff)

PHYSICS 50. Astronomy Laboratory and Observational Astronomy
Introduction to observational astronomy emphasizing the use of optical telescopes. Observations of stars, nebulae, and galaxies in laboratory sessions with 16- and 24-inch telescopes at the Stanford Observatory. No previous physics required. Limited enrollment. Lab. GER: DB-NatSci
3 units, Aut (Funk, S), Sum (Staff)

PHYSICS 59. Current Research Topics
Recommended for prospective Physics majors. Presentations of current research topics by faculty with research interests related to physics, often including tours of experimental laboratories where the research is conducted.
1 unit, Aut (Allen, S)

PHYSICS 61. Mechanics and Special Relativity
(First in a three-part series: 61,63,65.) Advanced freshman physics. For students with a strong high school mathematics and physics background contemplating a major in Physics or interested in a rigorous treatment of physics. The fundamental structure of classical physics including Newtonian mechanics, electricity and magnetism, waves, optics, thermodynamics. Foundations of modern physics including special relativity, atomic structure, quantization of light, matter waves and the Schrödinger equation. Prerequisites: high school physics and familiarity with calculus (differentiation and integration in one variable). Pre- or corequisite: MATH 51. GER: DB-NatSci
4 units, Aut (Moler, K)

PHYSICS 63. Electricity, Magnetism, and Waves
(Second in a three-part series: 61,63,65.) Advanced freshman physics. For students with a strong high school mathematics and physics background contemplating a major in Physics or interested in a rigorous treatment of physics. The fundamental structure of classical physics including Newtonian mechanics, electricity and magnetism, waves, optics, thermodynamics. Foundations of modern physics including special relativity, atomic structure, quantization of light, matter waves and the Schrödinger equation. Prerequisites: high school physics and familiarity with calculus (differentiation and integration in one variable). Pre- or corequisite: MATH 52. GER: DB-NatSci
4 units, Win (Gratta, G)

PHYSICS 64. Advanced Electromagnetism Laboratory
Experimental work in mechanics, electricity and magnetism. Corequisite 63. (Staff)
1 unit, Win (Gratta, G)

PHYSICS 65. Thermodynamics and Foundations of Modern Physics
(Third in a three-part series: 61,63,65.) Advanced freshman physics. For students with a strong high school mathematics and physics background contemplating a major in Physics or interested in a rigorous treatment of physics. The fundamental structure of classical physics including Newtonian mechanics, electricity and magnetism, waves, optics, thermodynamics. Foundations of modern physics including special relativity, atomic structure, quantization of light, matter waves and the Schrödinger equation. Prerequisites: high school physics and familiarity with calculus (differentiation and integration in one variable). Pre- or corequisite: MATH 53. GER: DB-NatSci
4 units, Spr (Romani, R)

PHYSICS 67. Introduction to Laboratory Physics
Methods of experimental design, data collection and analysis, statistics, and curve fitting in a laboratory setting. Experiments drawn from electronics, optics, heat, and particle physics. Intended as preparation for PHYSICS 105, 107, 108. Lecture plus laboratory format. Required for 60 series Physics majors; recommended for 40 series students who intend to major in Physics. Corequisite: 65 or 43.
2 units, Spr (Pam, R)

PHYSICS 70. Foundations of Modern Physics
Required for Physics majors who completed the 40 series, or the PHYSICS 60 series prior to 2005-06. Special relativity, the experimental basis of quantum theory, atomic structure, quantization of light, matter waves, Schrödinger equation. Prerequisites: 41, 43. Corequisite: 45. Recommended: prior or concurrent registration in MATH 53. GER: DB-NatSci
4 units, Aut (Kasevich, M)

PHYSICS 80N. The Technical Aspects of Photography
(F,Sem) Stanford Introductory Seminar. Preference to freshmen and sophomores with some background in photography. How cameras record photographic images on film and electronically. Technical photographic processes to use cameras effectively. Camera types and their advantages, how lenses work and their limitations, camera shutters, light meters and the proper exposure of film, film types, depth of focus, control of the focal plane and perspective, and special strategies for macro and night photography. View cameras and range finder technical cameras. Students take photographs around campus. Prerequisite: high school physics.
3 units, Spr (Osheroff, D)

PHYSICS 83N. Physics in the 21st Century
(F,Sem) Stanford Introductory Seminar. Preference to freshmen. Current topics at the frontier of modern physics. Topics include subatomic particles and the standard model, symmetries in nature, extra dimensions of space, string theory, supersymmetry, the big bang theory of the origin of the universe, black holes, dark matter, and dark energy of the universe. Why the sun shines. Cosmology and inflation. GER: DB-NatSci
3 units, Aut (Kallosh, R)

PHYSICS 87N. The Physics of One: Nanoscale Science and Technology
(F,Sem) Stanford Introductory Seminar. Preference to freshmen. Contemporary interdisciplinary research in nanoscience and nanotechnology; the manipulation of nature's fundamental building blocks. Accomplishments and questions engendered by knowledge at the discrete limit of matter. Prerequisite: high school physics. GER: DB-NatSci
3 units, Win (Manoharan, H)

PHYSICS 100. Introduction to Observational and Laboratory Astronomy
For physical science or engineering students. Emphasis is on the quantitative measurement of astronomical parameters such as distance, temperature, mass, composition of stars, galaxies, and quasars. Observation using the 0.4m and 0.6m telescopes at the Stanford Observatory. Limited enrollment. Prerequisites: one year of college physics; prior or concurrent registration in 65, or 70; and consent of instructor. GER: DB-NatSci
4 units, Spr (Allen, S)

PHYSICS 105. Intermediate Physics Laboratory I: Analog Electronics
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 63.
3 units, Aut (Pam, R)

PHYSICS 107. Intermediate Physics Laboratory II: Experimental Techniques and Data Analysis
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 40 or 60 series, and 70 and 105. Recommended: 130, prior or concurrent enrollment in 120. WIM
4 units, Win (Kasevich, M)

PHYSICS 108. Intermediate Physics Laboratory III: Project
Small student groups plan, design, build, and carry out a single experimental project in low-temperature physics. Prerequisites 105, 107.
3 units, Win (Goldhaber-Gordon, D), Spr (Goldhaber-Gordon, D)

PHYSICS 110. Intermediate Mechanics
Lagrangian and Hamiltonian mechanics. Principle of least action, Galilean relativity, Lagrangian mechanical systems, Euler-Lagrange equations. Central potential, Kepler's problem, planetary motion. Scattering problems, disintegration, Rutherford scattering cross section. Harmonic motion in the presence of rapidly oscillating field. Poisson's brackets, canonical transformations, Liouville's theorem, Hamilton-Jacoby equation. Prerequisites: 41 or 61, and MATH 53
4 units, Spr (Kuo, C)

PHYSICS 112. Mathematical Methods of Physics
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 132 most pertinent to Physics majors. Prerequisites: MATH 50 or 50H series, and MATH 131.
4 units, Win (Kallosh, R)

SCHOOL OF HUMANITIES AND SCIENCES

PHYSICS 113. Computational Physics
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, prior or concurrent registration in 110, 121. Previous programming experience not required.
4 units, Spr (Cabrera, B)

PHYSICS 120. Intermediate Electricity and Magnetism
(First in a two-part series: 120,121.) Vector analysis, electrostatic fields, including multipole expansion. Dielectrics, static magnetic fields, magnetic materials. Maxwell's equation. Electromagnetic radiation. Special relativity and transformation between electric and magnetic fields. Plane wave problems (free space, conductors and dielectric materials, boundaries). Dipole and quadrupole radiation and their frequency and angular distributions. Scattering synchrotron and bremsstrahlung processes. Energy loss in water. Wave guides and cavities. Prerequisites: PHYSICS 43 or 63; concurrent or prior registration in MATH 52 and 53. Recommended: concurrent or prior registration in PHYSICS 112.
4 units, Win (Cabrera, B)

PHYSICS 121. Intermediate Electricity and Magnetism
(Second in a two-part series: 120,121.) Vector analysis, electrostatic fields, including multipole expansion. Dielectrics, static magnetic fields, magnetic materials. Maxwell's equation. Electromagnetic radiation. Special relativity and transformation between electric and magnetic fields. Plane wave problems (free space, conductors and dielectric materials, boundaries). Dipole and quadrupole radiation and their frequency and angular distributions. Scattering synchrotron and bremsstrahlung processes. Energy loss in water. Wave guides and cavities. Prerequisites: PHYSICS 120; concurrent or prior registration in MATH 131. Recommended: PHYSICS 112.
4 units, Spr (Petrosian, V)

PHYSICS 130. Quantum Mechanics
(First in a two part series: 130,131.) The origins of quantum mechanics, wave mechanics, and the Schrödinger equation. Heisenberg's matrix formulation of quantum mechanics, solutions to one-dimensional systems, separation of variables and the solution to three-dimensional systems, the central field problem and angular momentum eigenstates, spin and the coupling of angular momentum, Fermi and Bose statistics, time-independent perturbation theory. Prerequisites: PHYSICS 70, 110. Pre- or corequisites: PHYSICS 120, 121, and MATH 131.
4 units, Aut (Burchat, P)

PHYSICS 131. Quantum Mechanics
(Second in a two-part series: 130,131.) The origins of quantum mechanics, wave mechanics, and the Schrödinger equation. Heisenberg's matrix formulation of quantum mechanics, solutions to one-dimensional systems, separation of variables and the solution to three-dimensional systems, the central field problem and angular momentum eigenstates, spin and the coupling of angular momentum, Fermi and Bose statistics, time-independent perturbation theory. Prerequisites: PHYSICS 70, 110. Pre- or corequisites: PHYSICS 120, 121, and MATH 131.
4 units, Win (Bucksbaum, P)

PHYSICS 134. Advanced Topics in Quantum Mechanics
Variational principle, time-dependent perturbation theory, WKB approximation. Scattering theory: partial wave expansion, Born approximation. Nature of quantum measurement: EPR paradox, Bell's inequality, and Schrödinger's cat paradox. Additional topics may include relativistic quantum mechanics or quantum information science. Prerequisites: 130, 131.
4 units, Spr (Kahn, S)

PHYSICS 152A. Introduction to Particle Physics I
(Same as PHYSICS 252A) 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. Prerequisite: 130. Pre- or corequisite: 131.
3 units, Win (Burchat, P)

PHYSICS 152B. Introduction to Particle Physics II
(Same as PHYSICS 252B) Discoveries and observations in experimental particle physics and relation to theoretical developments. Asymptotic freedom. Charged and neutral weak interactions. Electroweak unification. Weak isospin. Gauge theories, spontaneous symmetry breaking and the Higgs mechanism. Quark and lepton mixing. CP violation. Neutrino oscillations. Prerequisites: 152 or 152A, 130, 131.
3 units, Spr (Gratta, G)

PHYSICS 160. Introduction to Stellar and Galactic Astrophysics
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. Prerequisites: 40 or 60 series, and 70.
3 units, Win (Petrosian, V)

PHYSICS 161. Introduction to Extragalactic Astrophysics and Cosmology
Observations of the distances and compositions of objects on cosmic scales: galaxies, galaxy clusters, quasars, and diffuse matter at high red shift. Big bang cosmology, physical processes in the early universe, the origin of matter and the elements, inflation, and creation of structure in the Universe. Observational evidence for dark matter and dark energy. Future of the Universe. Prerequisites: calculus and college physics at the level of the 40 or 60 series, and 70.
3 units, Spr (Wechsler, R)

PHYSICS 169A. Independent Study in Astrophysics and Honors Thesis: Selection of the Problem
Description of the problem, its background, work planned in the subsequent two quarters, and development of the theoretical apparatus or initial interpretation of the problem.
1-9 units, Aut (Staff)

PHYSICS 169B. Independent Study in Astrophysics and Honors Thesis: Continuation of Project
Substantial completion of the required computations or data analysis for the research project selected.
1-9 units, Win (Staff)

PHYSICS 169C. Independent Study in Astrophysics and Honors Thesis: Completion of Project
Completion of research and writing of a paper presenting methods used and results.
1-9 units, Spr (Staff)

PHYSICS 170. Thermodynamics, Kinetic Theory, and Statistical Mechanics
(First in a two-part series: 170,171.) 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; entropy; reversibility; applications to various properties of matter; absolute zero and low temperature phenomena. Distribution functions, transport phenomena, fluctuations, equilibrium between phases, phase changes, the partition function for classical and quantum systems, Bose-Einstein condensation, and the electron gas. Cooperative phenomena including ferromagnetism, the Ising model, and lattice gas. Irreversible processes. Corequisite: PHYSICS 130.
4 units, Aut (Goldhaber-Gordon, D)

PHYSICS 171. Thermodynamics, Kinetic Theory, and Statistical Mechanics
(Second in a two-part series: 170,171.) 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; entropy; reversibility; applications to various properties of

matter; absolute zero and low temperature phenomena. Distribution functions, transport phenomena, fluctuations, equilibrium between phases, phase changes, the partition function for classical and quantum systems, Bose-Einstein condensation, and the electron gas. Cooperative phenomena including ferromagnetism, the Ising model, and lattice gas. Irreversible processes. Corequisite: PHYSICS 131.

4 units, Win (Zhang, S)

PHYSICS 172. Solid State Physics
Crystal structures and bonding in solids. X-ray diffraction. Lattice dynamics and thermal properties. Electronic structure of solids; transport properties of metals; quantum oscillations; charge density waves. Properties and applications of semiconductors. Phenomenology and microscopic theory of superconductivity. Prerequisites: 170, 171.

3 units, Spr (Manoharan, H)

PHYSICS 190. Independent Study
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.

1-9 units, Aut (Staff), Win (Staff), Spr (Staff), Sum (Staff)

PHYSICS 204A. Seminar in Theoretical Physics
Topics of recent interest may include cosmology, black hole physics, and strong-weak coupling duality transformations. May be repeated for credit.

3 units, Aut (Laughlin, R)

PHYSICS 204B. Seminar in Theoretical Physics
Topics including quantum computing, Berry phase, and quantum Hall effect. May be repeated for credit.

3 units, Win (Doniach, S)

PHYSICS 205. Undergraduate Honors Research
Experimental or theoretical project and thesis in Physics under supervision of a faculty member. Planning of the thesis project should begin no later than middle of the junior year. Successful completion of an honors thesis leads to graduation with departmental honors. Prerequisites: superior work in Physics as an undergraduate major and approval of the honors adviser.

1-12 units, Aut (Staff), Win (Staff), Spr (Staff), Sum (Staff)

GRADUATE COURSES IN PHYSICS

PHYSICS 210. Advanced Particle Mechanics
The Lagrangian and Hamiltonian dynamics of particles. Beyond small oscillations. Phase portraits, Hamilton-Jacoby theory, action-angle variables, adiabatic invariance. Nonlinear dynamical systems, continuous and discrete. Behavior near the fixed points, stability of solutions, attractors, chaotic motion. Transition to continuum mechanics. Prerequisite: 110 or equivalent.

3 units, Aut (Kahn, S)

PHYSICS 211. Continuum Mechanics
Elasticity, fluids, turbulence, waves, gas dynamics, shocks, and MHD plasmas. Examples from everyday phenomena, geophysics, and astrophysics.

3 units, Win (Peskin, M)

PHYSICS 212. Statistical Mechanics
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: 130, 131, 171, or equivalents.

3 units, Spr (Susskind, L)

PHYSICS 216. Back of the Envelope Physics
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, some not included in a standard curriculum. Applications include properties of materials, fluid mechanics, geophysics, astrophysics, and cosmology. Prerequisites: undergraduate mechanics, statistical mechanics, electricity and magnetism, and quantum mechanics.

3 units, Aut (Zhang, S)

PHYSICS 220. Classical Electrodynamics
(First in a two part series: 220, 221) Electrostatics and magnetostatics: conductors and dielectrics, magnetic media, electric and magnetic forces, and energy. Maxwell's equations: electromagnetic waves, Poynting's theorem, electromagnetic properties of matter, dispersion relations, wave guides and cavities, magnetohydrodynamics. Special relativity: Lorentz transformations, covariant, equations of electrodynamics and mechanics, Lagrangian formulation, Noether's theorem and conservation laws. Radiation: dipole and quadrupole radiation, electromagnetic scattering and diffraction, the optical theorem, Liénard-Wiechert potentials, relativistic Larmor's formula, frequency and angular distribution of radiation, synchrotron radiation. Energy losses in matter: Bohr's formula, Cherenkov radiation, bremsstrahlung and screening effects, transition radiation. Prerequisites: 121, 210, or equivalents; MATH 106 and 132.

3 units, Win (Kapitulnik, A)

PHYSICS 221. Classical Electrodynamics
(Second in a two part series: 220,221) Electrostatics and magnetostatics: conductors and dielectrics, magnetic media, electric and magnetic forces, and energy. Maxwell's equations: electromagnetic waves, Poynting's theorem, electromagnetic properties of matter, dispersion relations, wave guides and cavities, magnetohydrodynamics. Special relativity: Lorentz transformations, covariant, equations of electrodynamics and mechanics, Lagrangian formulation, Noether's theorem and conservation laws. Radiation: dipole and quadrupole radiation, electromagnetic scattering and diffraction, the optical theorem, Liénard-Wiechert potentials, relativistic Larmor's formula, frequency and angular distribution of radiation, synchrotron radiation. Energy losses in matter: Bohr's formula, Cherenkov radiation, bremsstrahlung and screening effects, transition radiation. Prerequisite: PHYSICS 220 or equivalent.

3 units, Spr (Fetter, A)

PHYSICS 230. Quantum Mechanics
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: 131 or equivalent.

3 units, Aut (Shenker, S)

PHYSICS 231. Quantum Mechanics
Basis for higher level courses on atomic solid state and particle physics. Wigner-Eckart theorem and addition of angular momenta. 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: 230.

3 units, Win (Shenker, S)

PHYSICS 232. Quantum Mechanics
Special topics. Elementary excitations in solids (the free electron gas, electronic band structure, phonons). Elementary scattering theory (Born approximation, partial wave analyses, resonance scattering). Relativistic single-particle equations. Dirac equation applied to central potentials, relativistic corrections, and nonrelativistic limits.

3 units, Spr (Shenker, S)

PHYSICS 252A. Introduction to Particle Physics I
(Same as PHYSICS 152A) 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. Prerequisite: 130. Pre- or corequisite: 131.

3 units, Win (Burchat, P)

PHYSICS 252B. Introduction to Particle Physics II
(Same as PHYSICS 152B) Discoveries and observations in experimental particle physics and relation to theoretical developments. Asymptotic freedom. Charged and neutral weak interactions. Electroweak unification. Weak isospin. Gauge theories, spontaneous symmetry breaking and the Higgs mechanism. Quark and lepton mixing. CP violation. Neutrino oscillations. Prerequisites: 152 or 152A, 130, 131.
3 units, Spr (Gratta, G)

PHYSICS 260. Introduction to Astrophysics and Cosmology
The observed properties and theoretical models of stars, galaxies, and the universe. Physical processes for production of radiation from cosmic sources. Observations of cosmic microwave background radiation. Newtonian and general relativistic models of the universe. Physics of the early universe, nucleosynthesis, baryogenesis, nature of dark matter and dark energy and inflation. Prerequisites: 110, 121, and 171, or equivalents.
3 units, Aut (Petrosian, V)

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

PHYSICS 275. Electrons in Nanostructures
The behavior of electrons in metals or semiconductors at length scales below 1 micron, smaller than familiar macroscopic objects but larger than atoms. Ballistic transport, Coulomb blockade, localization, quantum mechanical interference, and persistent currents. Topics may include quantum Hall systems, graphen, spin transport, spin-orbit coupling in nanostructures, magnetic tunnel junctions, Kondo systems, and 1-dimensional systems. Readings focus on the experimental research literature, and recent texts and reviews. Prerequisite: undergraduate quantum mechanics and solid state physics.
3 units, alternate years, not given this year

PHYSICS 290. Research Activities at Stanford
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.
1-3 units, Aut (Zhang, S)

PHYSICS 291. Practical Training
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.
3 units, Aut (Staff), Win (Staff), Spr (Staff), Sum (Staff)

PHYSICS 293. Literature of Physics
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.
1-15 units, Aut (Staff), Win (Staff), Spr (Staff), Sum (Staff)

PHYSICS 294. Teaching of Physics Seminar
Required of all first-year Physics graduate students, plus other Teaching Assistants who are teaching Physics courses for the first time. Weekly seminar/discussions. Techniques for teaching physics, especially through interactive engagement. Review of Physics Education Research results. Simulated teaching situations. In-class observations and practice teaching.
1 unit, Aut (Pam, R)

PHYSICS 301. Astrophysics Laboratory
Seminar/lab. Astronomical observational techniques and physical models of astronomical objects. Observational component uses the 24-inch telescope at the Stanford Observatory and ancillary photometric and spectroscopic instrumentation. Emphasis is on spectroscopic and photometric observation of main sequence, post-main sequence, and variable stars. Term project developing observational equipment or software. Limited enrollment. Prerequisite: consent of instructor.
3 units, not given this year

PHYSICS 321. Laser Spectroscopy
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: 230. Recommended: 231.
3 units, alternate years, not given this year

PHYSICS 323. Laser Cooling and Trapping
Principles of laser cooling and atom trapping. Optical forces on atoms, forms of laser cooling, atom optics and atom interferometry, ultra-cold collisions, and introduction to Bose condensation of dilute gases. Emphasis is on the development of the general formalisms that treat these topics. Applications of the cooling and trapping techniques: atomic clocks, internal sensors, measurements that address high-energy physics questions, many-body effects, polymer science, and biology. Prerequisite: 231 or equivalent.
3 units, Spr (Kasevich, M)

PHYSICS 330. Quantum Field Theory
Quantization of scalar and Dirac fields. Introduction to supersymmetry. Feynman diagrams. Quantum electrodynamics. Elementary electrodynamic processes: Compton scattering; e+e- annihilation. Loop diagrams and electron (g-2). Prerequisites: 130, 131, or equivalents.
3 units, Aut (Devereaux, T)

PHYSICS 331. Quantum Field Theory
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: 330.
3 units, Win (Brodsky, S)

PHYSICS 332. Quantum Field Theory
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 330.
3 units, Spr (Wacker, J)

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

PHYSICS 360. Physics of Astrophysics
Theoretical concepts and tools for modern astrophysics. Radiation transfer equations; emission, scattering, and absorption mechanisms: Compton, synchrotron and bremsstrahlung processes; photoionization and line emission. Equations of state of ideal, interacting, and degenerate gasses. Application to astrophysical sources such as HII regions, supernova remnants, cluster of galaxies, and compact sources such as accretion disks, X-ray, gamma-ray, and radio sources. Prerequisites: 121, 171 or equivalent.
3 units, not given next year

PHYSICS 362. Advanced Extragalactic Astrophysics and Cosmology
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, 211, and 260 or 360.
3 units, Win (Wechsler, R)

PHYSICS 363. Solar and Solar-Terrestrial Physics
Structure, mechanisms, and properties of the Sun's interior and atmosphere. Tools for solar observations; magnetic fields and polarimetry. Solar oscillations and helioseismology. Differential rotation and turbulent convection. Solar MHD, Alfven and magneto-acoustic waves. Solar cycle and dynamo. Magnetic energy release, reconnection, particle acceleration. Solar activity, sunspots, flares, coronal mass ejections; UV, X-ray, and high-energy particle emissions. The interaction of the solar wind with Earth's magnetosphere and its terrestrial effects; space weather. Prerequisite: 221 or equivalent.
3 units, not given this year

PHYSICS 364. Advanced Gravitation
Early universe cosmology. Topics at the interface between cosmology and gravity, particle theory, and speculative theories of physics at the Planck scale such as string theory. Inflationary cosmology and generation of density pertubations, models of baryogenesis, big bang nucleosynthesis, and speculations about the Universe at the Planck scale. Experiments in the near future that may extend or revise current notions.
3 units, not given this year

PHYSICS 370. Theory of Many-Particle Systems
Application of quantum field theory to the nonrelativistic, many-body problem, including methods of temperature-dependent Green's functions and canonical transformations. Theory of finite-temperature, interacting Bose and Fermi systems with applications to superfluidity, superconductivity, and electron gas. Prerequisite: 232.
3 units, not given this year

PHYSICS 372. Condensed Matter Theory I
Fermi liquid theory, many-body perturbation theory, response function, functional integrals, interaction of electrons with impurities. Prerequisite: APPPHYS 273 or equivalent.
3 units, Aut (Kivelson, S)

PHYSICS 373. Condensed Matter Theory II
Superfluidity and superconductivity. Quantum magnetism. Prerequisite: 372.
3 units, Win (Laughlin, R)

PHYSICS 376. Superfluidity and Superconductivity
Introduction to superfluid He: two-fluid model, phonons, and rotons, Feynman description, vortices, Bogoliubov theory. Phenomenology of superconductors: London description, Ginzburg-Landau model, type-I vs. type-II materials, Josephson effects, thin films, Kosterlitz-Thouless behavior, electron-phonon coupling. BCS theory: bulk systems, tunneling, strong-coupling materials, dirty and gapless superconductivity, fluctuation effects, Ginzburg criterion. Recommended: APPPHYS 272, 273, or equivalents.
3 units, not given this year

PHYSICS 450. Particle Physics at the Large Hadron Collider
General properties of proton-proton collisions at 14 TeV. Capabilities of the LHC experiments. QCD predictions for hard-scattering reactions: parton distributions, radiative corrections, jets, parton shower. Methods for computing multijet cross sections. Properties of W, Z, top quarks, and Higgs bosons at the LHC. Methods for discovering new heavy particles. May be repeated for credit. Prerequisite: PHYSICS 262, 330, 331, and 332.
3 units, not given this year

PHYSICS 451. Physics Beyond the Standard Model I.
Electroweak anomalies, electroweak baryon number violation, grand unification, SU(5), SO(10), gauge coupling unification, b-tau unification, proton decay, naturalness and the hierarchy problem; technicolor and extended technicolor; the supersymmetric Standard Model, supersymmetric unification. Prerequisites: Physics 330, 331, 332, 351
3 units, Win (Dimopoulos, S)

PHYSICS 452. Physics Beyond the Standard Model II
SUSY dark matter, SUSY flavor problem, universality and proportionality, theories of SUSY breaking, gauge mediation, gravity mediation, moduli problem, large extra dimensions and TeV scale gravity; the cosmological constant problem, Weinberg's solution and the landscape, split supersymmetry, decaying dark matter, axiverse. Prerequisites: PHYSICS 330, 331, 332, 351, 451.
3 units, Spr (Dimopoulos, S)

PHYSICS 463. Special Topics in Astrophysics: Theoretical Cosmology
This course is intended to provide a usable description of the application of general relativity to physical phenomena associated with spinning black holes and neutron stars with a view to providing illustrations and tests of the theory of strong field gravity. The topics covered will be: stationary axisymmetric metrics and stellar structure, orbits and rays, accretion disks, stellar companions, electromagnetic effects, gravitational radiation. Emphasis will be placed on developing practical calculational techniques. Prerequisite - Ph. 262 or equivalent.
3 units, Spr (Blandford, R)

PHYSICS 490. Research
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.
1-15 units, Aut (Staff), Win (Staff), Spr (Staff), Sum (Staff)