

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://exploreddegrees.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 offered Autumn and Spring Quarter, PHYSICS 43 Electricity and Magnetism offered Winter and Summer Quarter, and PHYSICS 45 Light and Heat in Autumn Quarter. While it is recommended that most students begin the sequence with PHYSICS 41 in Autumn 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 41E and PHYSICS 43A are optional 1 unit companion courses to PHYSICS 41 and PHYSICS 43 respectively. They provide 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.

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	How Things Work: An Introduction to Physics (not offered 2020-21)	3

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	1

Physics Placement Diagnostic

All students who would like to enroll in either PHYSICS 45 Light and Heat or PHYSICS 61 Mechanics and Special Relativity must take the Placement Diagnostic if they have never taken an Introductory Physics course at Stanford (i.e., not taken at least one of the following courses: PHYSICS 21, 23, 25, 41, 41A/E, 43, 45, 61, 63, 65).

All frosh must take the Placement Diagnostic to enroll in PHYSICS 41 Mechanics.

For more information, see the department's Physics Placement Diagnostic (<https://physics.stanford.edu/academics/undergraduate-students/placement-diagnostic/>) page.

Graduate Programs in Physics

Graduate students find opportunities for research in many areas of Physics. Faculty advisers are drawn from many departments, including, but not limited to Physics, Particle Physics and Astrophysics at SLAC, Photon Science at SLAC, Materials Science and Engineering, Electrical Engineering, and Biology.

The number of graduate students admitted to the Department of Physics is strictly limited. Students should submit applications by Tuesday, December 15, 2020 at 11:59 p.m. Pacific Time 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://exploreddegrees.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

Physics is concerned with a rigorous, mathematical understanding of the fundamental laws that govern our universe and everything in it. The Physics major provides students with a foundational understanding of the pillars of modern physics: mechanics, electromagnetic theory, quantum mechanics, and statistical mechanics. The major is designed around a range of tracks that allow students the flexibility to explore a particular interest in more depth, including but not limited to astrophysics, biophysics, computational physics, education, geophysics, and quantum information science.

Physics majors have gone on to pursue careers in basic or applied research, teaching, and policy, as well as many parts of the private sector as engineers, consultants, and founders of startups. Others have combined the Physics major with a minor or major in the humanities and pursued careers in the arts.

Physics majors often pursue advanced degrees, including coterminal master's degrees in EE, CS, Applied & Engineering Physics, Statistics and other fields, and Ph.D. programs in physics or other fields. Students who are specifically interested in preparing for a Ph.D. program in physics should see "Suggestions for students interested in pursuing a Ph.D. program in Physics or closely related fields (p. 6)" below.

Suggested Preparation for the Major

Prospective Physics majors are advised to take PHYSICS 59 Frontiers of Physics Research in their freshman or sophomore year.

How to Declare the Major in Physics

All prospective physics majors should take the Physics Placement Diagnostic web site (<https://physics.stanford.edu/academics/undergraduate-students/placement-diagnostic/>) to get sound advice on which introductory physics sequence will be sufficiently challenging without being overwhelming, and where to begin in that sequence. Prospective majors, especially those who are beginning the major during sophomore year, can contact the undergraduate program coordinator (elva@stanford.edu) to arrange an advising appointment. Students who have had previous college-level courses should make an advising appointment for placement and possible transfer credit. For additional information on Advanced Placement, see the Registrar's web site (<http://studentaffairs.stanford.edu/registrar/students/ap/>).

Degree Requirements

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. The only exceptions for which a grade of S or CR is acceptable are PHYSICS 42, 44, 46, 62, 64, 67, and one and only one of the following courses: PHYSICS 41, 43, 45, 61, 63, 65.

Each Physics major takes a set of required courses common to all tracks, followed by an additional six courses in one of eight defined tracks or, in rare cases, an individually designed track.

See these sample four-year plans (<https://docs.google.com/spreadsheets/d/1KlJk8-EMStYKC3YqPvgdfsnwCq-ybSpF-XwFACfH-4/edit/#gid=1959434091>) that illustrate how to complete the required courses for all tracks for different starting points in the math and physics sequences.

Course Requirements

	Units	
Introductory Sequence	16-20	
Complete either the 40 Series or the 60 Series ¹		
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	
Required Math Courses	21-24	
Complete MATH 50 or 60CM Series:		
50-Series		
MATH 51	Linear Algebra, Multivariable Calculus, and Modern Applications	
MATH 52	Integral Calculus of Several Variables	
MATH 53	Ordinary Differential Equations with Linear Algebra	
60CM-Series		
MATH 61CM	Modern Mathematics: Continuous Methods	
MATH 62CM	Modern Mathematics: Continuous Methods	
MATH 63CM	Modern Mathematics: Continuous Methods	
Complete one course from:		
PHYSICS 111	Partial Differential Equations of Mathematical Physics	
MATH 131P	Partial Differential Equations	
MATH 173	Theory of Partial Differential Equations ²	
Intermediate Physics Sequence		
PHYSICS 120	Intermediate Electricity and Magnetism I	4
PHYSICS 121	Intermediate Electricity and Magnetism II	4
PHYSICS 130	Quantum Mechanics I	4

PHYSICS 170	Thermodynamics, Kinetic Theory, and Statistical Mechanics I	4
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Writing in the Major (WIM)

PHYSICS 191	Scientific Communication in Physics ³	
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Physics Track

Select one of the tracks defined below and complete six courses for the selected track. Physics, math and practicum elective course options for each track are listed here. 24

Physics Elective Options

Any Physics (PHYSICS) or Applied Physics (APPPHYS) course of 3 or more units, numbered 100 and above not including PHYSICS 190, 198, 199, 201, 205, 240, 241, 290, 291, 293, 294, and APPPHYS 100, APPPHYS 290, APPPHYS 291, APPPHYS 390, or any APPPHYS course numbered 400 or higher)

Math Elective Options

Any Math (MATH) course 101 and above (not 197), 3 units or more. Or any of the following

PHYSICS 112	Mathematical Methods for Physics
CS 109	Introduction to Probability for Computer Scientists

STATS 116 Theory of Probability

EE 261 The Fourier Transform and Its Applications

Practicum Course Options

PHYSICS 100 Introduction to Observational Astrophysics

PHYSICS 104 Electronics and Introduction to Experimental Methods

PHYSICS 105 Intermediate Physics Laboratory I: Analog Electronics (Course not offered this year)

PHYSICS 106 Experimental Methods in Quantum Physics

PHYSICS 107 Intermediate Physics Laboratory II: Experimental Techniques and Data Analysis (Course not offered this year)

PHYSICS 108 Advanced Physics Laboratory: Project (Course not offered this year)

PHYSICS 113 Computational Physics

PHYSICS 166 Statistical Methods in Experimental Physics

Total Units 77-84

¹ Although not generally recommended, students with sufficient lab preparation who do not take all three required introductory lab courses may substitute an extra advanced lab course (PHYSICS 100, 104, 105, 106, 107, or 108) for all three required introductory labs. Note that in this case, taking any of the introductory labs does not in any way reduce the requirement of taking an extra advanced lab. In general, only an extra advanced lab, not any other courses, may substitute for the intro labs. A student must apply to make this substitution using the usual course substitution form.

² In years when MATH 173 Theory of Partial Differential Equations is not offered, MATH 220 Partial Differential Equations of Applied Mathematics is a recommended alternative.

³ PHYSICS 107 Intermediate Physics Laboratory II: Experimental Techniques and Data Analysis qualifies for WIM if taken in 2019-20 or earlier.

Tracks

In addition to the courses listed above (required for all tracks), Physics majors must complete six additional courses as defined for one of the following tracks. A course taken to satisfy the general requirements above cannot also count for a track requirement. Any course taken to satisfy a track requirement must be at least 3 units. Tracks are not

declarable in Axxess; they do not appear on the transcript nor on the diploma.

A letter grade of 'C-' or higher is required for all courses in each Physics track; therefore, any course in another department that does not offer a letter grade cannot count towards the requirement for a Physics track, even if the course is listed as an option for a track.

Click on the name of the track to see detailed requirements:

Core Track

Recommended starting point for students considering applying to Ph.D. programs in physics; see below for further advice (p. 6).

		Units
Required		
PHYSICS 110	Advanced Mechanics	3-4
PHYSICS 131	Quantum Mechanics II	4
PHYSICS 171	Thermodynamics, Kinetic Theory, and Statistical Mechanics II	4
Complete one practicum course		
Complete one Physics elective		
Complete one additional physics or math elective course		

Astrophysics

		Units
PHYSICS 100	Introduction to Observational Astrophysics	4
PHYSICS 110	Advanced Mechanics	3-4
PHYSICS 160	Introduction to Stellar and Galactic Astrophysics	3
PHYSICS 161	Introduction to Cosmology and Extragalactic Astrophysics	3
or PHYSICS 262	General Relativity	
PHYSICS 171	Thermodynamics, Kinetic Theory, and Statistical Mechanics II	4
Complete one course from:		3
PHYSICS 113	Computational Physics	
PHYSICS 166	Statistical Methods in Experimental Physics	
PHYSICS 262	General Relativity	

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

Biophysics

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

		Units
PHYSICS 110	Advanced Mechanics	3-4
or PHYSICS 131	Quantum Mechanics II	
PHYSICS 171	Thermodynamics, Kinetic Theory, and Statistical Mechanics II	4
Complete one course from:		
One Practicum Course		
APPPHYS 232	Advanced Imaging Lab in Biophysics	4
Complete three courses from:		
APPPHYS 205	Introduction to Biophysics	3-4
or BIO 126	Introduction to Biophysics	
APPPHYS 237	Quantitative Evolutionary Dynamics and Genomics	3

or BIO 251	Quantitative Evolutionary Dynamics and Genomics	
APPPHYS 293	Theoretical Neuroscience	3
or PSYCH 242	Theoretical Neuroscience	
APPPHYS 294	Cellular Biophysics	3
or BIO 294	Cellular Biophysics	
BIOE 42	Physical Biology	4
BIOE 101	Systems Biology	3
BIOE 102	Physical Biology of Macromolecules	4

Computational Physics and Data Science

		Units
PHYSICS 110	Advanced Mechanics	3-4
PHYSICS 113	Computational Physics	4
One Physics Elective Course		
Complete three courses from:		
PHYSICS 166	Statistical Methods in Experimental Physics	3
or STATS 116	Theory of Probability	
or CS 109	Introduction to Probability for Computer Scientists	
CS 129	Applied Machine Learning	3-4
CS 154	Introduction to the Theory of Computation	3-4
CS 161	Design and Analysis of Algorithms	3-5
CS 205L	Continuous Mathematical Methods with an Emphasis on Machine Learning	3
CS 221	Artificial Intelligence: Principles and Techniques	3-4
CS 229	Machine Learning	3-4
CS 230	Deep Learning	3-4
STATS 200	Introduction to Statistical Inference	4
STATS 203	Introduction to Regression Models and Analysis of Variance	3
or STATS 270	A Course in Bayesian Statistics	
or STATS 271	Applied Bayesian Statistics	

Geophysics

		Units
PHYSICS 110	Advanced Mechanics	3-4
PHYSICS 131	Quantum Mechanics II	4
or PHYSICS 171	Thermodynamics, Kinetic Theory, and Statistical Mechanics II	
One Practicum Course		
Complete three courses from:		
GEOPHYS 110	Introduction to the Foundations of Contemporary Geophysics	3
GEOPHYS 120	Ice, Water, Fire	3-5
GEOPHYS 128	MODELING EARTH	3-4
GEOPHYS 130	Introductory Seismology	3
GEOPHYS 162		3-4
GEOPHYS 165	Ice Penetrating Radar	1-3
GEOPHYS 182	Reflection Seismology	3
GEOPHYS 184	Journey to the Center of the Earth	3
GEOPHYS 188	Basic Earth Imaging	2-3
GEOPHYS 227	Global Seismology	3
GEOPHYS 237	Evolution of Terrestrial Planets	3

Mathematical Physics

		Units
PHYSICS 110	Advanced Mechanics	3-4
One Practicum Course		
Two Math Elective Courses		
Two Physics or Math Elective Courses		

Physics Education

		Units
PHYSICS 110	Advanced Mechanics	3-4
PHYSICS 131	Quantum Mechanics II	4
or PHYSICS 171	Thermodynamics, Kinetic Theory, and Statistical Mechanics II	
One Practicum Course		
Complete three courses from:		
PHYSICS 295	Learning & Teaching of Science ((Recommended))	3
or EDUC 280	Learning & Teaching of Science	
EDUC 101	Introduction to Teaching and Learning	4
EDUC 398	Core Mechanics for Learning	3
EDUC 400A	Introduction to Statistical Methods in Education	3-4
EDUC 266	Educational Neuroscience	3
EDUC 332	Theory and Practice of Environmental Education	3
EDUC 357	Science and Environmental Education in Informal Contexts	3-4
EDUC 218	Topics in Cognition and Learning: Technology and Multitasking	3
EDUC 328	Topics in Learning and Technology: Core Mechanics for Learning	3
EDUC 391	Engineering Education and Online Learning	3

Quantum Science and Information

		Units
PHYSICS 131	Quantum Mechanics II	4
PHYSICS 134	Advanced Topics in Quantum Mechanics	3-4
PHYSICS 110	Advanced Mechanics	3-4
or PHYSICS 171	Thermodynamics, Kinetic Theory, and Statistical Mechanics II	
One Practicum Course		
Complete two courses from:		
APPPHYS 225	Probability and Quantum Mechanics	3
APPPHYS 228	Quantum Hardware	4
CS 154	Introduction to the Theory of Computation	3-4
CS 259Q/269Q	Quantum Computing	3
EE 276	Information Theory	3
or STATS 376A	Information Theory	

Individually Designed Track

In rare cases, a student may propose a new track. The proposed courses must have a theme (rather than being a disconnected set of courses), and they should either include physics content, benefit from a physics perspective, deepen the student's understanding of physics, or allow students to apply their physics knowledge more broadly. The proposal should be as specific as possible and include detailed rationale for the track. The proposed track must not be largely redundant with an existing track or major. The proposal should address feasibility

issues such as whether the proposed courses are offered with sufficient frequency.

Other Information

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.

Additional Information

Suggestions for students interested in pursuing a Ph.D. program in Physics or closely related fields

Research in physics is roughly divided into fields that include astrophysics, atomic, molecular and optical (AMO) physics, biophysics, condensed matter physics, and particle physics. Physics research at Stanford includes computational, experimental, observational, and theoretical work in these fields. It can be useful to consult with faculty in each of the research areas that you might be interested in pursuing in graduate school since recommendations for preparation often vary by field. See the Physics Research Areas webpage (<https://physics.stanford.edu/research/research-areas/>) to get started.

The above requirements are the minimum for the Physics major; they are intended to provide a foundation in math and physics that prepares students for the very wide range of careers pursued by Physics majors. However, if a student is considering pursuing a Ph.D. program in Physics, the department recommends that they complete more than the required Math and Physics courses in a track. In particular, they should take PHYSICS 110, 131, 134, and 171, which are necessary elements of undergraduate Physics in preparation for Ph.D. programs.

The department also recommends acquiring laboratory experience, e.g., courses such as PHYSICS 100, 104, 105, 106, 107, or 108, or research experience in an experimental laboratory. It also recommends completing additional Physics and Math courses based on the student's interests and the advice of faculty in their field(s) of interest. In addition, they should pursue research in physics, e.g., through the Undergraduate Summer Research program (<https://physics.stanford.edu/academics/undergraduate-students/undergraduate-summer-research/>) in the Physics department, or through research opportunities outside Stanford (<https://physics.stanford.edu/academics/undergraduate-students/summer-research/research-opportunities-outside-stanford/>).

The department strongly recommend that students consult with their Physics major advisor (and faculty in any research area in which they are interested) for recommendations on courses and research or internship opportunities, and attend the faculty-led group advising meetings held near the end of Autumn Quarter on applying for summer research, and in the Autumn and Spring quarters on thinking about advanced degrees.

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.

How to Declare the Minor in Physics

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.

Physics Concentration

Degree Requirements

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.

Course Requirements

	Units
An undergraduate minor in Physics requires a minimum of 25 units with the following course work:	
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 65 & PHYSICS 67	Quantum and Thermal Physics and Introduction to Laboratory Physics	
PHYSICS 63 & PHYSICS 64	Electricity, Magnetism, and Waves and Electricity, Magnetism and Waves Laboratory	
At least three PHYSICS courses numbered 100 or above from the following courses: PHYSICS 100, 105, 107, 108, 110, 111, 112, 113, 120, 121, 130, 131, 134, 152, 160, 161, 166, 170, 171, 172, 182, 199, 211, 212, 216, 220, 230, 231, 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	5
PHYSICS 50	Astronomy Laboratory and Observational Astronomy	3-4
or PHYSICS 100	Introduction to Observational Astrophysics	
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		22-23

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://exploreddegrees.stanford.edu/graduatedegrees/>)" section of this bulletin, include completion of 45 units of unduplicated course work after the bachelor's degree. Course taken to fulfill the degree requirements below must be taken for a letter grade. 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://exploreddegrees.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. All courses taken to fulfill the Physics Ph.D. degree requirements must be taken for a letter grade, except for PHYSICS 290 and PHYSICS 294 which are only offered for Satisfactory/No Credit.

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
PHYSICS 111	Partial Differential Equations of Mathematical Physics	4
PHYSICS 112	Mathematical Methods for Physics	4

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://exploreddegrees.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. Courses must be taken for a letter grade. 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.

COVID-19 Policies

On July 30, the Academic Senate adopted grading policies effective for all undergraduate and graduate programs, excepting the professional Graduate School of Business, School of Law, and the School of Medicine M.D. Program. For a complete list of those and other academic policies relating to the pandemic, see the "COVID-19 and Academic Continuity (<http://exploreddegrees.stanford.edu/covid-19-policy-changes/#tempdeptemplatetabtext>)" section of this bulletin.

The Senate decided that all undergraduate and graduate courses offered for a letter grade must also offer students the option of taking the course for a "credit" or "no credit" grade and recommended that deans, departments, and programs consider adopting local policies to count courses taken for a "credit" or "satisfactory" grade toward the fulfillment of degree-program requirements and/or alter program requirements as appropriate.

Undergraduate Degree Requirements

Grading

The Department of Physics counts all courses taken in academic year 2020-21 with a grade of 'CR' (credit) or 'S' (satisfactory) towards satisfaction of undergraduate degree requirements that otherwise require a letter grade.

Course Requirements

Students who take PHYSICS 61 and PHYSICS 63 in Autumn and Winter quarters may take either PHYSICS 65 in Summer 2021 or EE 65 in Spring 2021 to complete the requirement of an introductory physics sequence for the Physics major.

For all undergraduates who entered Stanford in Autumn 2019, the requirement to take PHYSICS 44 or PHYSICS 67 for the Physics major is waived as these courses were not offered in Spring 2020. This does not change the other introductory lab requirements.

Graduate Degree Requirements

Grading

The Department of Physics counts all courses taken in academic year 2020-21 with a grade of 'CR' (credit) or 'S' (satisfactory) towards satisfaction of graduate degree requirements that otherwise require a letter grade.

Other Graduate Policies

The Department of Physics will conduct doctoral candidacy reviews as scheduled in Spring Quarter 2020-21.

Qualifying exams will continue to be administered in Spring Quarter 2020-21. Students may request an extension by writing to the Director of Graduate Studies.

Graduate Advising Expectations

The Department of Physics is committed to providing academic advising in support of graduate student scholarly and professional development. When most effective, this advising relationship entails collaborative and sustained engagement by both the adviser and the advisee. As a best practice, advising expectations should be periodically discussed and reviewed to ensure mutual understanding. Both the adviser and the advisee are expected to maintain professionalism and integrity.

Faculty advisers guide students in key areas such as selecting courses, designing and conducting research, developing of teaching pedagogy, navigating policies and degree requirements, and exploring academic opportunities and professional pathways.

Graduate students are active contributors to the advising relationship, proactively seeking academic and professional guidance and taking responsibility for informing themselves of policies and degree requirements for their graduate program.

For a statement of University policy on graduate advising, see the "Graduate Advising (<http://exploreddegrees.stanford.edu/graduatedegrees/#advisingandcredentialstext>)" section of this bulletin.

Emeriti: (Professors) Sebastian Doniach, Alexander L. Fetter, William A. Little, Douglas D. Osheroff, 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; (Professor, Courtesy) Peter A. Sturrock (Applied Physics), Richard Taylor (SLAC National Accelerator Laboratory)

Chair: Shamit Kachru

Director of Undergraduate Studies: Peter Graham

Director of Graduate Studies: Sean Hartnoll

Professors: Tom Abel, Steven Allen, Roger Blandford, Phil Bucksbaum, Patricia Burchat, Blas Cabrera, Steven Chu, Sarah Church, Persis Drell, Savas G. Dimopoulos, David Goldhaber-Gordon, Giorgio Gratta, Patrick Hayden, Kent Irwin, Shamit Kachru, Steven Kahn, Renata E. Kallosh, Aharon Kapitulnik, Mark Kasevich, Steven A. Kivelson, Chao-Lin Kuo, Robert B. Laughlin, Andrei D. Linde, Bruce Macintosh, Kathryn Moler, Peter F. Michelson, Vahe Petrosian, Xiao-liang Qi, Roger W. Romani, Zhi-Xun Shen, Stephen Shenker, Eva Silverstein, Leonard Susskind, Risa Wechsler, Carl Wieman

Associate Professors: Peter Graham, Sean Hartnoll, Benjamin Lev, Hari Manoharan, Srinivas Raghu, Monika Schleier-Smith, Leonardo Senatore, Douglas Stanford (untentured)

Assistant Professors: Benjamin Feldman, Jason Hogan, Vedika Khemani, Lauren Tompkins

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

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

Lecturers: Julien Devin, Chaya Nanavati, Rick Pam

Adjunct Professor: Adam Brown, Ralph DeVoe, Steve Yellin

Courses

PHYSICS 14N. Quantum Information: Visions and Emerging Technologies. 3 Units.

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

PHYSICS 15. Stars and Planets in a Habitable Universe. 3 Units.

Is the Earth unique in our galaxy? Students learn how stars and our galaxy have evolved and how this produces planets and the conditions suitable for life. Discussion of the motion of the night sky and how telescopes collect and analyze light. The life-cycle of stars from birth to death, and the end products of that life cycle -- from dense stellar corpses to supernova explosions. Course covers recent discoveries of extrasolar planets -- those orbiting stars beyond our sun -- and the ultimate quest for other Earths. Intended to be accessible to non-science majors, material is explored quantitatively with problem sets using basic algebra and numerical estimates. Sky observing exercise and 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 19. How Things Work: An Introduction to Physics. 3 Units.

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

PHYSICS 21. Mechanics, Fluids, and Heat. 4 Units.

How are the motions of objects and the behavior of fluids and gases determined by the laws of physics? Students learn to describe the motion of objects (kinematics) and understand why objects move as they do (dynamics). Emphasis on how Newton's three laws of motion are applied to solids, liquids, and gases to describe diverse phenomena. 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. 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 interactive group problem solving. Prerequisite: high school algebra and trigonometry; calculus not required. Autumn 2020-21: Class will be taught remote synchronously in active learning format with much of the learning in smaller breakout rooms that will not be recorded. Please enroll in a section that you can attend regularly.

PHYSICS 21S. Mechanics and Heat. 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. 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. In this unusual pandemic year we have planned remote lab activity for you. These labs are a mix of online labs as well as hands-on exercises you can do at home, in a dorm or wherever you may be. The class will be structured with an online Zoom section, where you and others in your section will meet with a TA and go over your results, and do some group exercises. You can do the online materials with a virtual lab partner, we encourage you to get the benefit of someone to collaborate on your analysis and observations. We will be sending every enrolled student a kit of hands-on lab materials, you will get more details the first week of class.

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 and Optics. 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. 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 40. Vector and Mathematical Analysis for Mechanics. 2 Units.

Physics 40 teaches fundamental math and physics concepts that are important for success in Physics 41+ and engineering statics/dynamics. This class has a strong emphasis on physics problem solving schema and vector and mathematical analysis for geometry, forces, and motion. Students master both geometric and algebraic representations of vectors, resolving vectors into components, vector addition/subtraction, dot-products, cross-products, and derivatives. Through systematic practice, students translate between various representations, e.g. sketches, descriptions of a physical system, equations, graphs, and real systems (from various physics and engineering disciplines). Vector equations are used to generate scalar equations, which are then solved using analytical or easy-to-use online tools. Physics 40 is an on-ramp to Physics 41 for students with little high school physics. The minimum corequisite is Math 20 (or equivalent). A permission number is required to enroll. Contact mitiguy@stanford.edu.

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. Spring 2020-21: Class will be taught remote synchronously in active learning format with much of the learning in smaller breakout rooms so class will not be recorded. Please enroll in a section that you can attend regularly. In order to register for this class all FROSH must complete the Physics Placement Diagnostic at <https://physics.stanford.edu/academics/undergraduate-students/placement-diagnostic>. Students who complete the Physics Placement Diagnostic by 3 PM (Pacific) on Friday will have their hold lifted over the weekend. Minimum prerequisites: High school physics and MATH 20 (or high school calculus if sufficiently rigorous). Minimum co-requisite: MATH 21 or equivalent. Since high school math classes vary widely, it is recommended that you take at least one math class at Stanford before or concurrently with taking Physics 41. In addition, it is recommended that you take Math 51 or CME 100 before taking the next course in the Physics 40 series, Physics 43.

PHYSICS 41E. Mechanics, Concepts, Calculations, and Context. 5 Units.

Physics 41E (Physics 41 Extended) is an 5-unit version of Physics 41 (4 units) for students with little or no high school physics or calculus. Course topics and mathematical complexity are identical to Physics 41, but the extra classroom time allows students to engage with concepts, develop problem solving skills, and become fluent in mathematical tools that include vector representations and operations, and calculus. The course will use problems drawn from everyday life to explore important physical principles in mechanics, such as Newton's Laws of motion, equations of kinematics, and conservation of energy and momentum. Prerequisite: Math 19 or equivalent; Co-requisite: Math 20 or equivalent. In order to register for this class students must EITHER have already taken an introductory Physics class (20, 40, or 60 sequence) or have taken the Physics Placement Diagnostic at <https://physics.stanford.edu/academics/undergraduate-students/placement-diagnostic>. Enrollment is via permission number which can be obtained by filling in the application at https://stanforduniversity.qualtrics.com/jfe/form/SV_2fNzeSljoYtKiln.

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. In this unusual pandemic year we have planned remote lab activity for you. These labs are a mix of online labs as well as hands-on exercises you can do at home, in a dorm or wherever you may be. The class will be structured with an online Zoom section, where you and others in your section will meet with a TA and go over your results, and do some group exercises. You can do the online materials with a virtual lab partner, we encourage you to get the benefit of someone to collaborate on your analysis and observations. We will be sending every enrolled student a kit of hands-on lab materials, you will get more details the first week of class.

PHYSICS 43. Electricity and Magnetism. 4 Units.

What is electricity? What is magnetism? How are they related? How do these phenomena manifest themselves in the physical world? The theory of electricity and magnetism, as codified by Maxwell's equations, underlies much of the observable universe. Students develop both conceptual and quantitative knowledge of this theory. Topics include: electrostatics; magnetostatics; simple AC and DC circuits involving capacitors, inductors, and resistors; integral form of Maxwell's equations; electromagnetic waves. Principles illustrated in the context of modern technologies. Broader scientific questions addressed include: How do physical theories evolve? What is the interplay between basic physical theories and associated technologies? Discussions based on the language of mathematics, particularly differential and integral calculus, and vectors. Physical understanding fostered by peer interaction and demonstrations in lecture, and discussion sections based on interactive group problem solving. Prerequisite: PHYSICS 41 or equivalent. MATH 21 or MATH 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. Corequisite: PHYSICS 43-34 or PHYSICS 43-35; Prerequisite: application at https://stanforduniversity.qualtrics.com/jfe/form/SV_da1PUm1scvnQ5IV.

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. In order to register for this class students must EITHER have already taken an introductory Physics class (20, 40, or 60 sequence) or have taken the Physics Placement Diagnostic at <https://physics.stanford.edu/academics/undergraduate-students/placement-diagnostic>. Prerequisite: PHYSICS 41 or equivalent. MATH 21 or MATH 51 or CME 100 or equivalent.

PHYSICS 45N. Topics in Light and Heat. 1 Unit.

Preference to freshmen. Explores the quantum and classical properties of light from stars, lasers and other sources. Includes modern applications ranging from gravity wave interferometers to x-ray lasers.

PHYSICS 46. Light and Heat Laboratory. 1 Unit.

Hands-on exploration of concepts in geometrical optics, wave optics and thermodynamics. Pre- or corequisite: PHYSICS 45. In this unusual pandemic year we have planned remote lab activity for you. These labs are a mix of online labs as well as hands-on exercises you can do at home, in a dorm or wherever you may be. The class will be structured with an online Zoom section, where you and others in your section will meet with a TA and go over your results, and do some group exercises. You can do the online materials with a virtual lab partner, we encourage you to get the benefit of someone to collaborate on your analysis and observations. We will be sending every enrolled student a kit of hands-on lab materials, you will get more details the first week of class.

PHYSICS 50. Astronomy Laboratory and Observational Astronomy. 3 Units.

Introduction to observational astronomy emphasizing the use of optical telescopes. Observations of stars, nebulae, and galaxies in laboratory sessions with 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. In order to register for this class students must EITHER have already taken an introductory Physics class (20, 40, or 60 sequence) or have taken the Physics Placement Diagnostic at <https://physics.stanford.edu/academics/undergraduate-students/placement-diagnostic>. Recommended prerequisites: Mastery of mechanics at the level of AP Physics C and AP Calculus BC or equivalent. Corequisite: MATH 51 or MATH 61CM or MATH 61DM.

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. In this unusual pandemic year we have planned remote lab activity for you. These labs are a mix of online labs as well as hands-on exercises you can do at home, in a dorm or wherever you may be. The class will be structured with an online Zoom section, where you and others in your section will meet with a TA and go over your results, and do some group exercises. You can do the online materials with a virtual lab partner, we encourage you to get the benefit of someone to collaborate on your analysis and observations. We will be sending every enrolled student a kit of hands-on lab materials, you will get more details the first week of class.

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 or MATH 61CM. Pre- or corequisite: MATH 52 or MATH 62CM.

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 thermodynamics 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. Topics related to quantum mechanics include: atoms, electrons, nuclei. Experimental evidence for physics that is not explained by classical mechanics and E&M. 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. Particle-in-a-box, simple harmonic oscillator, barrier penetration, tunneling. Topics related to thermodynamics: limitations of classical mechanics in describing systems with a very large number of particles. Ideal gas, equipartition, heat capacity, definition of temperature, entropy. Brief introduction to kinetic theory and statistical mechanics. Maxwell speed distribution, ideal gas in a box. Laws of thermodynamics. Cycles, heat engines, free energy. Prerequisites: PHYSICS 61 & PHYSICS 63.

PHYSICS 67. Introduction to Laboratory Physics. 1 Unit.

Methods of experimental design, data collection and analysis, statistics, curve fitting and model validation used in experimental science. Study of common data analysis techniques drawn via example measurements from electronics, optics, heat, and modern physics. Lecture format only for AY2020/2021. Required for PHYSICS 60 series Physics and Engineering Physics majors; recommended 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. Schrödinger 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 tsunamis, 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. This course provides an in-depth examination of frontiers of physics research, including fundamental physics, cosmology, and physics of the future. Questions such as: What is the universe made of? What is the nature of space, time, and matter? What can we learn about the history of the universe and what does it tell us about its future? A large part of 20th century was defined by revolutions in physics & everyday applications of electromagnetism, relativity, and quantum mechanics. What other revolutions can physics bring to human civilization in the 21st century? What is quantum computing? What can physics say about consciousness? What does it take to visit other parts of the solar system, or even other stars? 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. 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 physics research 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 93SI. Beyond the Laboratory: Physics, Identity, and Society. 1-2 Unit.

Beyond its laws and laboratories, what can physics teach us about society and ourselves? How do physicists' identities impact the types of scientific questions that are asked throughout history? And who do we call a physicist? This course seeks to address questions such as these, with an eye to understanding how physics relates to history, politics, and our own identities as young researchers. Students will develop a broader appreciation for where physics comes from, how it relates to themselves, and how they can shape its future. No prior knowledge of physics is necessary; all voices are welcome to contribute to the discussion about these big ideas. As an optional addendum to 93SI, students can participate in POISE (Physics Outreach through Inclusive Science Education), an intensive spring break program in which the themes discussed during the course will be explored in more depth. During POISE, students will develop short workshops for high school students that are geared towards making Physics interesting and accessible. In addition, we will take frequent off-campus trips to Bay Area national labs, museums, companies, the beach, camping sites, and more! Our intention is to create a retreat-style experience in which students can learn more about themselves and each other as Physicists, and put their knowledge to good use in the classroom. Those wishing to participate in the spring break component should apply here, <https://goo.gl/forms/KA0A0aCjD7QxxVbW2>, and expect to be enrolled in 2 units. Those who are interested in only the course component should apply here, <https://goo.gl/forms/xlrsDP0V2ESkMnbS2>, and expect to be enrolled in 1 unit.

PHYSICS 94SI. Diverse Perspectives in Physics. 1 Unit.

Have you ever wondered what it is like to be a professor, or what you could do with physics beyond academia? Do you want to hear about the life stories of people with diverse backgrounds who have studied or are studying physics? Professors and industry researchers possessing a diverse set of identities and backgrounds will share their journey in physics and their career trajectories, emphasizing their personal lives and experiences as undergraduates and graduate students. A Q&A session will follow. A free meal will be provided each session!

PHYSICS 95Q. The Philosophies of Three Great Physicists. 3 Units.

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

PHYSICS 96N. Harmony and the Universe. 3 Units.

Harmony is a multifaceted concept that has profoundly connects music, mathematics, physics, philosophy, physiology, and psychology. We will explore the evolution of our understanding of harmony and its immediate application in the function of musical instruments, and employ it as a nexus to understand its role in revolutionary scientific advances in gravity, relativity, quantum mechanics, and cosmology. In these explorations, we will examine some of the fundamental mathematical tools which provide us our current understanding of harmony. We will also see how the some concepts surrounding harmony are in tension, if not conflict, and how some great thinkers have followed them down down blind alleys and dead ends. The aim of the course is to show the enormous consequences of harmony in the evolution of our understanding of the universe, and how science itself progresses in fits, starts, and setbacks as old ideas intermingle with new developments. We will also see how objective/quantitative aspects of harmony interact with subjective/qualitative considerations, and how cultural perspectives and prejudices can affect the progression of science.

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 where student teams propose and execute an observational astronomy project of their choosing, using techniques learned in class to gather and analyze their data, and presenting their findings in the forms of professional-style oral presentations and research papers. Enrollment by permission. To get a permission number please complete form: <http://web.stanford.edu/~elva/physics100prelim.fb> If you have not heard from us by the beginning of class, please come to the first class session.

PHYSICS 104. Electronics and Introduction to Experimental Methods. 4 Units.

Introductory laboratory electronics, intended for Physics and Engineering Physics majors but open to all students with science or engineering interests in analog circuits, instrumentation and signal processing. The first part of the course is focused on hands-on exercises that build skills needed for measurements, including input/output impedance concepts, filters, amplifiers, sensors, and fundamentals of noise in physical systems. Lab exercises include DC circuits, RC and diode circuits, applications of operational amplifiers, optoelectronics, synchronous detection, and noise in measurements. The second portion of the class is an instrumentation design project, where essential instrumentation for a practical lab measurement is designed, constructed and applied for an experiment. Example measurements can include temperature measurement in a cryostat, resistivity measurement of a superconducting material, measurement of the 2-D position of an optical beam, development of a high impedance ion probe and clamp for neuroscience, or other projects of personal interest. The course focuses on practical techniques and insight from the lab exercises, with a goal to prepare undergraduates for laboratory research. No formal electronics experience is required beyond exposure to concepts from introductory Physics or Engineering courses (Ohm's law, charge conservation, physics of capacitors and inductors, etc.). Recommended prerequisite: Physics 43 and 44 or Physics 63 and 64, or Engineering 40A or 40M.

PHYSICS 105. Intermediate Physics Laboratory I: Analog Electronics. 4 Units.

Introductory laboratory electronics, designed for Physics and Engineering Physics majors but open to all students with science or engineering interests in analog circuits, instrumentation and signal processing. The course is focused on laboratory exercises that build skills needed for measurements, including sensors, amplification and filtering, and fundamentals of noise in physical systems. The hands-on lab exercises include DC circuits, RC and diode circuits, applications of operational amplifiers, non-linear circuits and optoelectronics. The class exercises build towards a lock-in amplifier contest where each lab section designs and builds a synchronous detection system to measure a weak optical signal, with opportunities to understand the limits of the design, build improvements and compare results with the other lab sections. The course focuses on practical techniques and insight from the lab exercises, with a goal to prepare undergraduates for laboratory research. No formal electronics experience is required beyond exposure to concepts from introductory Physics or Engineering courses (Ohm's law, charge conservation, physics of capacitors and inductors, etc.). Recommended prerequisite: Physics 43 or 63, or Engineering 40A or 40M.

PHYSICS 106. Experimental Methods in Quantum Physics. 4 Units.

Experimental physics lab course aimed at providing an understanding of and appreciation for experimental methods in physics, including the capabilities and limitations, both fundamental and technical. Students perform experiments that use optics, lasers, and electronics to measure fundamental constants of nature, perform measurements at the atomic level, and analyze results. Goals include developing an understanding of measurement precision and accuracy through concepts of spectral-analysis of coherent signals combined with noise. We explore the fundamental limits to measurement set by thermal noise at finite temperature, as well as optical shot-noise in photo-detection that sets the standard quantum limit in detecting light. Spectroscopy of light emitted from atoms reveals the quantum nature of atomic energy levels, and when combined with theoretical models provides information on atomic structure and fundamental constants of nature (e.g. the fine structure constant that characterizes the strength of all electro-magnetic interactions, and the ratio of the electron mass to the proton mass, m_e/m_p). Experiments may include laser spectroscopy to determine the interatomic potential, effective spring constant, and binding energy of a diatomic molecule, or measure the speed of light. This course will provide hands-on experience with semiconductor diode lasers, basic optics, propagation and detection of optical beams, and related electronics and laboratory instrumentation. For lab notebooks the class uses an integrated online environment for data analysis, curve fitting, (system is based on Jupyter notebooks, Python, and document preparation). Prerequisites: PHYSICS 40 series and PHYSICS 70, or 60 series, PHYSICS 120, PHYSICS 130; some familiarity with basic electronics is helpful but not required. Very basic programming in Python is needed, but background with Matlab, Origin, or similar software should be sufficient to come up to speed for the data analysis.

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. 5 Units.

Have you ever wanted to dream up a research question, then design, execute, and analyze an experiment to address it, together with a small group of your fellow students? This is an accelerated, guided experimental research experience, resembling real frontier research. Phenomena that have been studied include magnetization of ferromagnets, quantum hall effect in graphene, interference in superconducting circuits, loss in nanomechanical resonators, and superfluidity in helium. But most projects pursued (drawn from condensed matter and recently also particle physics) have never been done in the class before. Our equipment and apparatus for Physics 108 are very flexible, not standardized like in most other lab classes. We provide substantial resources to help your team. Often, with instructors' help, students obtain unique samples from Stanford research groups. Prerequisite: PHYSICS 105, or other experience in electronics. Suggested but less critical: Physics 130 (many phenomena you might study build on quantum mechanics) and Physics 107 (experience with data analysis and useful measurement tools: lock-in amplifier, spectrum analyzer.) We recommend taking this class in junior year if possible, as it can inform post-graduation decisions and can empower the professor to write a powerful letter of recommendation.

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 or PHYSICS 111. Recommended prerequisite: PHYSICS 130. Same as: PHYSICS 210

PHYSICS 111. Partial Differential Equations of Mathematical Physics. 4 Units.

This course is intended to introduce students to the basic techniques for solving partial differential equations that commonly occur in classical mechanics, electromagnetism, and quantum mechanics. Tools that will be developed include separation of variables, Fourier series and transforms, and Sturm-Liouville theory. Examples (including the heat equation, Laplace equation, and wave equation) will be drawn from different areas of physics. Through examples, students will gain a familiarity with some of the famous special functions arising in mathematical physics. Prerequisite: MATH 53 or 63. Completing PHYSICS 40 or 60 sequences helpful.

PHYSICS 112. Mathematical Methods for Physics. 4 Units.

The course will focus on nonlinear dynamics and chaos and its applications in physics and other areas of science. Topics will include first-order differential equations and bifurcations, phase plane analysis, limit cycles, chaos, iterated maps, period doubling, fractals, and strange attractors. Applications will be drawn from traditional areas of physics as well as fields like systems biology, evolutionary game theory, and sociophysics. This course can be repeated for credit. Prerequisites: MATH 53 or equivalent.

PHYSICS 113. Computational Physics. 4 Units.

Numerical methods for solving problems in mechanics, astrophysics, electromagnetism, quantum mechanics, and statistical mechanics. Methods include numerical integration; solutions of ordinary and partial differential equations; solutions of the diffusion equation, Laplace's equation and Poisson's equation with various methods; statistical methods including Monte Carlo techniques; matrix methods and eigenvalue problems. Short introduction to Python, which is used for class examples and active learning notebooks; independent class projects make up more than half of the grade and may be programmed in any language such as C, Python or Matlab. No Prerequisites but some previous programming experience is advisable.

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: PHYS 111, 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 quadrupole radiation. Special relativity and transformation between electric and magnetic fields. Prerequisites: PHYS 120 and PHYS 111 or MATH 131P or MATH 173; Recommended: PHYS 112.

PHYSICS 130. Quantum Mechanics I. 4 Units.

The origins of quantum mechanics and wave mechanics. Schrödinger equation and solutions for one-dimensional systems. Commutation relations. Generalized uncertainty principle. Time-energy uncertainty principle. Separation of variables and solutions for three-dimensional systems; application to hydrogen atom. Spherically symmetric potentials and angular momentum eigenstates. Spin angular momentum. Addition of angular momentum. Prerequisites: PHYSICS 65 or PHYSICS 70 and PHYSICS 111 or 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, PHYSICS 111 or 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 153. Introduction to String Theory, Quantum Gravity, and Black Holes. 3 Units.

This course will begin with a basic introduction to the physics and mathematics of string theory and its relation to gravity. Following that we will study the quantum mechanics of black holes, and how string theory has impacted our understanding of these extreme gravitational objects. Prerequisites: 130 and 131.

PHYSICS 155. Accelerators and Beams: Tools of Discovery and Innovation. 3 Units.

Particle accelerators range in scale from sub-mm structures created using lithography on a silicon chip to the 27-km Large Hadron Collider in Switzerland based on superconducting magnets. Some accelerators generate beams that are only nanometers in size while others are used to make the brightest x-ray beams in the world. Accelerators are used for medicine, security, and industry as well as discovery science. A recent study shows that nearly 30% of the Nobel Prizes in Physics had a direct contribution from accelerators. This course will cover the fundamentals of particle beam acceleration and control. Topics will include radio-frequency acceleration, alternate gradient focusing, and collective effects where electromagnetic fields from the particle beam act back on the beam or on adjacent beams. Some experimental studies of beam physics may be performed at the SLAC National Accelerator Laboratory. Prerequisites: Special relativity at the level of Physics 61 or 70, or equivalent. Physics 120 and 121, or EE 142 and 242; Physics 121/EE 142 can be taken concurrently with class.

PHYSICS 160. Introduction to Stellar and Galactic Astrophysics. 3 Units. Radiative processes. 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. Pre-requisite: Physics 120 or permission of instructor. Recommended: Some familiarity with plotting and basic numerical calculations.

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 166. Statistical Methods in Experimental Physics. 3 Units.

Statistical methods constitute a fundamental tool for the analysis and interpretation of experimental physics data. In this course, students will learn the foundations of statistical data analysis methods and how to apply them to the analysis of experimental data. Problem sets will include data-sets from real experiments and require the use of programming tools to extract physics results. Topics include probability and statistics, experimental uncertainties, parameter estimation, confidence limits, and hypothesis testing. Students will be required to complete a final project. Same as: PHYSICS 266

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 182. Quantum Gases. 3 Units.

Introduction to the physics of quantum gases and their use in quantum simulation and computation. Topics in modern atomic physics and quantum optics will be covered, including laser cooling and trapping, ultracold collisions, optical lattices, ion traps, cavity QED, quantum phase transitions in quantum gases and lattices, BEC and quantum degenerate Fermi gases, 1D and 2D quantum gases, dipolar gases, and quantum nonequilibrium dynamics and phase transitions. Prerequisites: undergraduate quantum and statistical mechanics courses. Applied Physics 203 strongly recommended but not required. Same as: APPPHYS 282, PHYSICS 282

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 191. Scientific Communication in Physics. 3 Units.

Development and practice of effective scientific communication in physics, including scientific publications, research proposals, science writing for a general audience, and effective communication of data. The course will involve extensive writing, reviewing, and revision, including responding effectively to critiques. Satisfies the WIM requirement for Physics and Engineering Physics majors. Intended for juniors and seniors. Prerequisites: two years of college level physics (e.g., completion of Physics 121).

PHYSICS 198. Learning Assistant Training Seminar. 1 Unit.

Training seminar for undergraduate students selected for the Learning Assistant (LA) program. In this seminar LAs learn and practice pedagogical techniques they will apply in an active learning classroom. LAs practice instruction strategies in a collaborative small group setting, with regular reflection and feedback. In addition, LAs learn mentoring practices to help fellow undergraduates develop academic skills. The seminar meets 90 minutes weekly with additional readings and reflection outside of class.

PHYSICS 199. The Physics of Energy and Climate Change. 3 Units.

Topics include measurements of temperature and sea level changes in the climate record of the Earth, satellite atmospheric spectroscopy, satellite gravity geodesy measurements of changes in water aquifers and glaciers, and ocean changes. The difference between weather fluctuations changes and climate change, climate models and their uncertainties in the context of physical, chemical and biological feedback mechanisms to changes in greenhouse gases and solar insolation will be discussed. Energy efficiency, transmission and distribution of electricity, energy storage, and the physics of harnessing fossil, wind, solar, geothermal, fission and fusion will be covered, along with prospects of future technological developments in energy use and production. Prerequisite: Physics 40 or Physics 60 series.

Same as: PHYSICS 201

PHYSICS 201. The Physics of Energy and Climate Change. 3 Units.

Topics include measurements of temperature and sea level changes in the climate record of the Earth, satellite atmospheric spectroscopy, satellite gravity geodesy measurements of changes in water aquifers and glaciers, and ocean changes. The difference between weather fluctuations changes and climate change, climate models and their uncertainties in the context of physical, chemical and biological feedback mechanisms to changes in greenhouse gases and solar insolation will be discussed. Energy efficiency, transmission and distribution of electricity, energy storage, and the physics of harnessing fossil, wind, solar, geothermal, fission and fusion will be covered, along with prospects of future technological developments in energy use and production. Prerequisite: Physics 40 or Physics 60 series.

Same as: PHYSICS 199

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 or PHYSICS 111. 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. 2 Units.

This course will deal with order of magnitude or approximate, low-tech approaches to estimating physical effects in various systems. One goal is to promote a synthesis of understanding of basic physics (including quantum mechanics, electromagnetism, and physics of fluids) through solving various classic problems. A special feature of the class this year will be a new format, where students will develop and present many of the lectures in close consultation with the faculty instructor. This is intended to both enhance learning, and to keep the interactive nature of instruction front and center in a quarter where lectures are delivered over zoom.

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 223. Stochastic and Nonlinear Dynamics. 3 Units.

Theoretical analysis of dynamical processes: dynamical systems, stochastic processes, and spatiotemporal dynamics. Motivations and applications from biology and physics. Emphasis is on methods including qualitative approaches, asymptotics, and multiple scale analysis. Prerequisites: ordinary and partial differential equations, complex analysis, and probability or statistical physics. Same as: APPPHYS 223, BIO 223, BIOE 213

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 interconvertibility. 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. Prerequisites: 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. Radiative processes. 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. Pre-requisite: Physics 120 or permission of instructor. Recommended: Some familiarity with plotting and basic numerical calculations. 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 266. Statistical Methods in Experimental Physics. 3 Units. Statistical methods constitute a fundamental tool for the analysis and interpretation of experimental physics data. In this course, students will learn the foundations of statistical data analysis methods and how to apply them to the analysis of experimental data. Problem sets will include data-sets from real experiments and require the use of programming tools to extract physics results. Topics include probability and statistics, experimental uncertainties, parameter estimation, confidence limits, and hypothesis testing. Students will be required to complete a final project. Same as: PHYSICS 166

PHYSICS 268. Physics with Neutrinos. 3 Units. Relativistic fermions, Weyl and Dirac equations, Majorana masses. Electroweak theory, neutrino cross sections, neutrino refraction in matter, MSW effect. Three-flavor oscillations, charge-parity violation, searches for sterile neutrinos, modern long- and short-baseline oscillation experiments. Seesaw mechanism, models of neutrino masses, lepton flavor violation. Neutrinoless double beta decay. Cosmological constraints on neutrino properties. Advanced topics, such as collective oscillations in supernovae or ultrahigh energy neutrinos, offered as optional projects. The material in this course is largely complementary to PHYS 269, focusing on particle physics aspects of neutrinos. Prerequisites: PHYSICS 121, 131 and 171 or equivalent. PHYS 230-231, 269, 152 and 161 or equivalent are helpful, but not required.

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

PHYSICS 275. Electrons in Nanostructures. 3 Units. The strange 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, persistent currents, graphene, topological insulators, 1D wires. After a few background lectures, students come to each class session prepared to discuss one or more classic review articles or recent experimental publications. Prerequisite: undergraduate quantum mechanics and solid state physics preferred; physicists, engineers, chemists welcome.

PHYSICS 282. Quantum Gases. 3 Units. Introduction to the physics of quantum gases and their use in quantum simulation and computation. Topics in modern atomic physics and quantum optics will be covered, including laser cooling and trapping, ultracold collisions, optical lattices, ion traps, cavity QED, quantum phase transitions in quantum gases and lattices, BEC and quantum degenerate Fermi gases, 1D and 2D quantum gases, dipolar gases, and quantum nonequilibrium dynamics and phase transitions. Prerequisites: undergraduate quantum and statistical mechanics courses. Applied Physics 203 strongly recommended but not required. Same as: APPPHYS 282, PHYSICS 182

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. Curricular Practical Training. 1-3 Unit. Curricular practical training for students participating in an internship with a physics-related focus. Meets the requirements for curricular practical training for students on F-1 visas. Prior to the internship, students submit a concise description of the proposed project and work activities. After the internship, students submit a summary of the work completed and skills learned, including a reflection on the professional growth gained as a result of the internship. This course may be repeated for credit. Students are responsible for arranging their own internship/employment and faculty sponsorship. Register under faculty sponsor's section number.

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

PHYSICS 294. Teaching of Physics Seminar. 1 Unit.

Weekly seminar/discussions on interactive techniques for teaching physics. Practicum which includes class observations, grading and student teaching in current courses. Required of all Teaching Assistants prior to first teaching assignment. Mandatory attendance at weekly in-class sessions during first 5 weeks of the quarter; mandatory successful completion of all practicum activities. Students who do not hold a US Passport must complete the International Teaching/Course Assistant Screening Exam and be cleared to TA before taking the class. Details: <https://language.stanford.edu/programs/efs/languages/english-foreign-students/international-teachingcourse-assistant-screening>. Enrollment in PHYSICS 294 is by permission. To get a permission number please complete form: https://stanforduniversity.qualtrics.com/jfe/form/SV_7VVM88d1iMTw8Xr. If you have not heard from us by the beginning of class, please come to the first class session.

PHYSICS 295. Learning & Teaching of Science. 3 Units.

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

Same as: EDUC 280, ENGR 295, MED 270, VPTL 280

PHYSICS 301. Astrophysics Laboratory. 3 Units.

Designed for physics graduate students but open to all graduate 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 where student teams propose and execute an observational astronomy project of their choosing, using techniques learned in class to gather and analyze their data, and presenting their findings in the forms of professional-style oral presentations and research papers. Enrollment by permission. To get a permission number please complete form: <http://web.stanford.edu/~elva/physics301prelim.fbn> If you have not heard from us by the beginning of class, please come to the first class session.

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 360. Modern Astrophysics. 3 Units.

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

PHYSICS 361. Cosmology and Extragalactic Astrophysics. 3 Units.

Intended as a complement to Ph 362 and Ph 364. Galaxies (including their nuclei), clusters, stars and backgrounds in the contemporary universe. Geometry, kinematics, dynamics, and physics of the universe at large. Evolution of the universe following the epoch of nucleosynthesis. Epochs of recombination, reionization and first galaxy formation. Fluid and kinetic description of the growth of structure with application to microwave background fluctuations and galaxy surveys. Gravitational lensing. The course will feature interleaved discussion of theory and observation. Undergraduate exposure to general relativity and cosmology at the level of Ph 262 and Ph 161 will be helpful but is not essential.

PHYSICS 362. The Early Universe. 3 Units.

Intended to complement PHYSICS 361, this course will cover the earlier period in cosmology up to and including nucleosynthesis. The focus will be on high energy, early universe physics. This includes topics such as inflation and reheating including generation of density perturbations and primordial gravitational waves, baryogenesis mechanisms, out of equilibrium particle production processes in the early universe e.g. both thermal and non-thermal production mechanisms for dark matter candidates such as WIMPs and axions, and production of the light nuclei and neutrinos. Techniques covered include for example out of equilibrium statistical mechanics such as the Boltzmann equation, and dynamics of scalar fields in the expanding universe. Other possible topics if time permits may include cosmological phase transitions and objects such as monopoles and primordial black holes. We will use quantum field theory, although it will hopefully be accessible for those without much background in that area. Suggested prerequisites: general relativity at the level of PHYSICS 262, some knowledge of cosmology and in particular the basics of FRW cosmology as in PHYSICS 361 for example, and some knowledge of quantum field theory e.g. at the level of PHYSICS 331 as a corequisite.

PHYSICS 364. Gravitational Radiation, Black Holes and Neutron Stars. 3 Units.

General relativistic theory of spinning black holes and neutron stars including accretion, jets and tidal capture. Direct and indirect observation of relativistic effects in active galactic nuclei and stellar sources. Linear theory of the generation and propagation of (non-primordial) gravitational radiation. Detection of gravitational waves by Michelson interferometers, pulsars and atom interferometers. Nonlinear emission by binary black holes. Nuclear equation of state and nucleosynthetic implications of neutron star binaries. Pre-requisite: Ph 262 or equivalent.

PHYSICS 366. Statistical Methods in Astrophysics. 3 Units.

Foundations of principled inference from data, primarily in the Bayesian framework, organized around applications in astrophysics and cosmology. Topics include probabilistic modeling of data, parameter constraints and model comparison, numerical methods including Markov Chain Monte Carlo, and connections to frequentist and machine learning frameworks. The course is organized around tutorials and a final project, providing hands-on experience with real data. Prerequisite: programming in Python or a similar language at the level of CS 106A. Recommended but not required: probability at the level of STATS 116 or PHYSICS 166/266.

PHYSICS 367. Special Topics in Astrophysics: Structure Formation and Galaxy Formation. 2 Units.

How does structure form in the Universe, and how do galaxies form within that structure? Topics will include the dependence of structure formation on cosmological parameters and the nature of dark matter, the key astrophysical processes involved in galaxy formation, and the connection between matter and galaxies. Current outstanding problems in structure formation and galaxy formation and the modern techniques used to address them will be highlighted. Course will include reading current literature and hands on computational problems. Recommended prerequisite: PHYSICS 261 or equivalent.

PHYSICS 368. Computational Cosmology and Astrophysics. 2 Units.

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

PHYSICS 372. Condensed Matter Theory I. 3 Units.

Fermi liquid theory, many-body perturbation theory, response function, functional integrals, interaction of electrons with impurities. Prerequisite: APPPHYS 273 or equivalent.

PHYSICS 373. Condensed Matter Theory II. 3 Units.

Superfluidity and superconductivity. Quantum magnetism. Prerequisite: PHYSICS 372.

PHYSICS 450. Advanced Theoretical Physics I: Random Matrices in Physics. 3 Units.

This course will survey some of the basic ideas and techniques in the theory of random matrices. These will be interspersed with discussions of some of the physical applications of these ideas including: energy spectra of quantum chaotic systems and the Eigenstate Thermalization Hypothesis; entanglement entropies; and aspects of 2D quantum gravity.

PHYSICS 451. Advanced Theoretical Physics II: Quantum Information Theory, Complexity, Gravity and Black Holes. 3 Units.

This course will cover the developing intersection between quantum information theory and the quantum theory of gravity. We will focus on the central roles of entanglement and computational complexity in black hole physics. Prerequisites: Basic knowledge of quantum mechanics, quantum field theory, and general relativity.

PHYSICS 455. Introductory Seminar on Recent Developments in Theoretical Physics. 1 Unit.

This seminar is for first-year graduate students interested in theoretical physics. It is driven by introductory-level student talks and focuses on recent foundational developments across the field. Typical areas of interest include cosmology, particle physics, string theory, quantum gravity, and condensed matter.

PHYSICS 470. Topics in Modern Condensed Matter Theory I: Many Body Quantum Dynamics. 3 Units.

Many body quantum systems can display rich emergent dynamical phenomena far from thermal equilibrium, whose understanding represents an exciting frontier of research at the interface of condensed matter, statistical physics, high energy theory and quantum information. This course is intended to serve as an introduction to this active research area, assuming only a knowledge of quantum mechanics and statistical physics. Topics covered include: quantum thermalization, many-body localization, quantum entanglement and its dynamics, tensor network methods, dynamical quantum phases and phase transitions, and Floquet theory. Prerequisites: PHYSICS 113, PHYSICS 130, PHYSICS 131, PHYSICS 170, and PHYSICS 171.

PHYSICS 471. Topics in Modern Condensed Matter Theory II: Open Problems in the theory of metals & superconductor. 3 Units.

We will begin by reviewing a modern perspective on the theory of conventional (BCS s-wave) and unconventional (e.g. d-wave) superconductors. We will then discuss a variety of issues that are of current interest, but which are either incompletely understood or entirely open problems in the field. Depending upon the interests of the class and the whims of the instructor, topics to be covered may include: quantum superconductor to insulator and superconductor to metal transitions, emergence of superconductivity from a non-Fermi liquid normal state, exotic superconducting phases of matter, interplay between superconductivity and other broken symmetry states (issues of ζ intertwined orders), and superconductivity in paradigmatic models of highly correlated electron systems, including problems in which there is an interplay between strong electron-electron and electron-phonon interactions. We will also touch on theoretical ideas - all of them currently still being explored and hence controversial - concerning theories of unconventional metallic states - i.e. metallic states that cannot be well described in the context of a theory of weakly interacting quasiparticles. While the subject matter of this course is motivated by ongoing experimental studies in a variety of quantum materials and devices, the principle focus of the class will be on a coherent understanding of what is known and on crisply identifying what is not known.

PHYSICS 490. Research. 1-18 Unit.

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

PHYSICS 491. Symmetry and Quantum Information. 2 Units.

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

PHYSICS 492. Topological Quantum Computation. 2 Units.

This course will be an introduction to topological quantum computation (TQC), which has recently emerged as an exciting approach to constructing fault-tolerant quantum computers. We start with a review of some basics of quantum computing, 2D topological phases of matter, Abelian/non-Abelian anyons, etc. Then we introduce the concept of TQC and study some examples such as the toric/surface code and Levin-Wen string-net model. We continue to talk about the mathematical theory of anyons including modular tensor categories, braid groups, 6j-symbols, Pentagon Equations. We study the issue of universality for different systems. Lastly, we show the equivalence of TQC with standard circuit model. Additional topics include complexity classes, Jones polynomials, topological field theories, etc. Prerequisite: Basic knowledge of quantum mechanics and condensed matter physics. Some knowledge of category theory and representation theory is useful but is not required. The course will run the first five weeks.

PHYSICS 801. TGR Project. 0 Units.

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PHYSICS 802. TGR Dissertation. 0 Units.

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