Physics

The department aims to develop in its students a comprehensive grasp of the principles of physics, together with a productive capacity in research. The courses of study are flexible in subject matter and are conducted by means of lectures, seminars, laboratories, and colloquia. Undergraduate as well as graduate students have opportunities to carry out research in fields of current interest.

The principal research fields of the department are condensed matter physics, elementary particle physics, low-temperature physics, nonlinear optics, physical acoustics, astrophysics, biological physics, and cosmology. Interdisciplinary study and research, coordinated with other departments, is encouraged for students interested in brain and neural science, semiconductor physics, geophysics, physics of solid continua, polymer physics, and computational physics, as well as other fields.

For additional information, please visit the department's website: http://www.brown.edu/academics/physics/

Physics Concentration Requirements

Physics is the scientific study of the fundamental principles governing the behavior of matter and the interaction of matter and energy. Mathematics is used to describe fundamental physical principles, the behavior of matter, and the interactions of matter and energy. As the most fundamental of sciences, physics provides a foundation for other scientific fields as well as the underpinnings of modern technology. The Physics department is unique because of the breadth of its faculty expertise and research, and the relatively intimate size of its classes above the introductory level. Physics concentrators may choose to pursue either the A.B. or the more intensive Sc.B. degree. Course work on either path covers a broad base of topics (for example, electricity and magnetism, classical and quantum mechanics, thermodynamics, and statistical mechanics). The Sc.B. degree requires additional advanced topics as well as a senior thesis project.

Standard concentration for the A.B. degree

Select one of the following Series:		2
PHYS 0030	Basic Physics A	
or PHYS 0050	Foundations of Mechanics	
or PHYS 0070	Analytical Mechanics	
PHYS 0040	Basic Physics B	
or PHYS 0060	Foundations of Electromagnetism and Modern Physics	
or PHYS 0160	Introduction to Relativity, Waves and Quantum Physics	
Take each of the following:		5
PHYS 0470	Electricity and Magnetism	
PHYS 0500	Advanced Classical Mechanics	
PHYS 0560	Experiments in Modern Physics	
PHYS 1410	Quantum Mechanics A	
PHYS 1530	Thermodynamics and Statistical Mechanics	
One additional 1000-level course or a mathematics course beyond the introductory level.		1
Total Credits		**8**

Standard program for the Sc.B. degree

Prerequisites:		
Select one of each:		2
PHYS 0050	Foundations of Mechanics	
or PHYS 0070	Analytical Mechanics	
PHYS 0060	Foundations of Electromagnetism and Modern Physics	
or PHYS 0160	Introduction to Relativity, Waves and Quantum Physics	
Select one of the following:		1
MATH 0190	Single Variable Calculus, Part II (Physics/ Engineering)	
or MATH 0090	Single Variable Calculus, Part I	
or MATH 0100	Single Variable Calculus, Part II	
Program:		**8**
PHYS 0470	Electricity and Magnetism	
PHYS 0500	Advanced Classical Mechanics	
PHYS 0560	Experiments in Modern Physics	
PHYS 1410	Quantum Mechanics A	
PHYS 1420	Quantum Mechanics B	
PHYS 1510	Advanced Electromagnetic Theory	
PHYS 1530	Thermodynamics and Statistical Mechanics	
PHYS 1560	Modern Physics Laboratory	
Take one additional 1000 or 2000 level Physics course or upper level course in related fields of science chosen by the student with the agreement of his or her advisor.		1
Four Mathematics courses beyond MATH 0190 or 0090, 0100 including choices from Applied Mathematics [1]		4
PHYS 1990	Senior Conference Course [2]	1
Total Credits		**17**

[1] In addition, courses in computer programming are recommended.

[2] A senior thesis is required. This is to be prepared in connection with PHYS 1990 under the direction of a faculty supervisor. The topic may be in related department or of interdisciplinary nature. In any event, a dissertation must be submitted.

Astrophysics Track for the Sc.B. degree

Prerequisites:		
Select one of each:		2
PHYS 0050	Foundations of Mechanics	
or PHYS 0070	Analytical Mechanics	
PHYS 0060	Foundations of Electromagnetism and Modern Physics	
or PHYS 0160	Introduction to Relativity, Waves and Quantum Physics	
PHYS 0270	Astronomy and Astrophysics	1
Select one of the following Series:		2
MATH 0170 & MATH 0180	Single Variable Calculus, Part II (Accelerated) and Multivariable Calculus	
MATH 0190 & MATH 0200	Single Variable Calculus, Part II (Physics/ Engineering) and Multivariable Calculus (Physics/ Engineering)	
MATH 0350	Multivariable Calculus With Theory (or equivalent)	
PHYS 0470	Electricity and Magnetism	1
Program:		
MATH 0520	Linear Algebra	1
or MATH 0540	Linear Algebra With Theory	
or PHYS 0720	Methods of Mathematical Physics	
Select one of the following Math courses:		1
APMA 0330	Methods of Applied Mathematics I	
APMA 0340	Methods of Applied Mathematics II	
APMA 0350	Applied Ordinary Differential Equations	
APMA 0360	Applied Partial Differential Equations I	
MATH 1110	Ordinary Differential Equations	
MATH 1120	Partial Differential Equations	

PHYS 0500	Advanced Classical Mechanics	1
PHYS 0560	Experiments in Modern Physics	1
PHYS 1410	Quantum Mechanics A	1
PHYS 1530	Thermodynamics and Statistical Mechanics	1
Three of the following:		3
PHYS 1100	General Relativity	
PHYS 1250	Stellar Structure and the Interstellar Medium	
PHYS 1270	Extragalactic Astronomy and High-Energy Astrophysics	
PHYS 1280	Introduction to Cosmology	
Two additonal 1000- or 2000-level courses in physics or a related field which are not listed as requirements.		2
PHYS 1990	Senior Conference Course [1]	1
Total Credits		**18**

[1] A senior thesis is required. This is to be prepared in connection with under the direction of a faculty supervisor. The topic may be in a related department or of interdisciplinary nature. In any event, a dissertation must be submitted.

Biological Physics Track for the Sc.B. degree

Foundations of Physics		
PHYS 0070	Analytical Mechanics	1
or PHYS 0050	Foundations of Mechanics	
or ENGN 0040	Engineering Statics and Dynamics	
PHYS 0160	Introduction to Relativity, Waves and Quantum Physics	1
or PHYS 0060	Foundations of Electromagnetism and Modern Physics	
PHYS 0470	Electricity and Magnetism	1
PHYS 0500	Advanced Classical Mechanics	1
PHYS 1410	Quantum Mechanics A	1
PHYS 1530	Thermodynamics and Statistical Mechanics	1
Select one of the following Series: [1]		1-2
Series A		
PHYS 0720	Methods of Mathematical Physics	
Series B		
Select one of the following:		
APMA 0330	Methods of Applied Mathematics I	
APMA 0350	Applied Ordinary Differential Equations	
MATH 1110	Ordinary Differential Equations	
And select one of the following:		
MATH 0180	Multivariable Calculus	
MATH 0200	Multivariable Calculus (Physics/ Engineering)	
MATH 0350	Multivariable Calculus With Theory	
MATH 0520	Linear Algebra	
MATH 0540	Linear Algebra With Theory	
Basic Biology and Chemistry		
BIOL 0200	The Foundation of Living Systems (or placement out of BIOL 0200)	1
BIOL 0500	Cell and Molecular Biology	1
CHEM 0330	Equilibrium, Rate, and Structure	1
Advanced Biophysical Topics and Techniques		
PHYS 1610	Biological Physics	1
PHYS 1990	Senior Conference Course	1
Elective Courses (four chosen from the following list, with at least two 1000-level courses, or additional courses approved by the concentration advisor:		**4**
APMA 0360	Applied Partial Differential Equations I	
APMA 0410	Mathematical Methods in the Brain Sciences	
APMA 0650	Introduction to Probability and Statistics	
APMA 1070	Quantitative Models of Biological Systems	
APMA 1080	Inference in Genomics and Molecular Biology	
BIOL 0280	Biochemistry	
BIOL 0470	Genetics	
BIOL 1050	Biology of the Eukaryotic Cell	
BIOL 1200	Protein Biophysics and Structure	
BIOL 1270	Advanced Biochemistry	
BIOL 1870	Techniques and Clinical Applications in Pathobiology	
CHEM 0350	Organic Chemistry I	
CHEM 0360	Organic Chemistry II	
MATH 0090	Single Variable Calculus, Part I	
MATH 0170	Single Variable Calculus, Part II (Accelerated)	
MATH 0190	Single Variable Calculus, Part II (Physics/ Engineering)	
MATH 1620	Mathematical Statistics	
MATH 1210	Probability	
PHYS 0560	Experiments in Modern Physics	
PHYS 1510	Advanced Electromagnetic Theory	
PHYS 1560	Modern Physics Laboratory	
PHYS 2620F	Selected Topics in Molecular Biophysics	
PHYS 1990	Senior Conference Course [2]	1
Total Credits		**17-18**

[1] Select Series A alone or two from Series B as indicated.

[2] A senior thesis is required. This is to be prepared in connection with under the direction of a faculty supervisor. The topic may be in a related department or of interdisciplinary nature. In any event, a dissertation must be submitted.

Mathematical Physics Track for the A.B. degree

Prerequisites:		
MATH 0090	Single Variable Calculus, Part I	1
or MATH 0100	Single Variable Calculus, Part II	
or MATH 0190	Single Variable Calculus, Part II (Physics/ Engineering)	
PHYS 0050	Foundations of Mechanics	1
or PHYS 0070	Analytical Mechanics	
Mathematics Courses [1]		
MATH 0180	Multivariable Calculus	1
or MATH 0200	Multivariable Calculus (Physics/Engineering)	
or MATH 0350	Multivariable Calculus With Theory	
MATH 0520	Linear Algebra	1
or MATH 0540	Linear Algebra With Theory	
MATH 1110	Ordinary Differential Equations	1
Select at least one of the following:		1
MATH 1060	Differential Geometry	
MATH 1120	Partial Differential Equations	
MATH 1210	Probability	
Physics Courses [1]		

PHYS 0060	Foundations of Electromagnetism and Modern Physics	1
or PHYS 0160	Introduction to Relativity, Waves and Quantum Physics	
PHYS 0470	Electricity and Magnetism	1
PHYS 0500	Advanced Classical Mechanics	1
PHYS 0560	Experiments in Modern Physics	1
Select at least two of the following:		2
PHYS 1410	Quantum Mechanics A	
PHYS 1420	Quantum Mechanics B	
PHYS 1510	Advanced Electromagnetic Theory	
PHYS 1530	Thermodynamics and Statistical Mechanics	
PHYS 1560	Modern Physics Laboratory	
Total Credits		**12**

[1] Concentrators are required to take at least one course in mathematics and one in physics in each of their last two semesters.

Mathematical Physics Track for the Sc.B. degree

Prerequisites:		
Select one of the following series:		2
PHYS 0050	Foundations of Mechanics	
or PHYS 0070	Analytical Mechanics	
PHYS 0060	Foundations of Electromagnetism and Modern Physics	
or PHYS 0160	Introduction to Relativity, Waves and Quantum Physics	
Select one of the following:		1-2
MATH 0190	Single Variable Calculus, Part II (Physics/ Engineering)	
MATH 0090 & MATH 0100	Single Variable Calculus, Part I and Single Variable Calculus, Part II	
Required courses:		
PHYS 0470	Electricity and Magnetism	1
PHYS 0500	Advanced Classical Mechanics	1
PHYS 0560	Experiments in Modern Physics	1
PHYS 1410	Quantum Mechanics A	1
PHYS 1530	Thermodynamics and Statistical Mechanics	1
MATH 0180 & MATH 0200	Multivariable Calculus and Multivariable Calculus (Physics/ Engineering)	1-2
or MATH 0350	Multivariable Calculus With Theory	
MATH 0520	Linear Algebra	1
or MATH 0540	Linear Algebra With Theory	
or PHYS 0720	Methods of Mathematical Physics	
MATH 1460	Complex Analysis	1
Four additional 1000 or 2000 level Physics courses		4
Two additional 1000 or 2000 level Math courses		2
PHYS 1990	Senior Conference Course [1]	1
Total Credits		**18-20**

[1] A senior thesis is required. This is to be prepared in connection with under the direction of a faculty supervisor.

Physics and Philosophy Concentration Requirements

The Physics and Philosophy concentration is for students with a deep interest in physics who do not need to acquire the laboratory and computational skills of a professional physicist. The concentration allows students to grapple with computational problems and deepen their investigation of conceptual and epistemological issues. By the end of the program, concentrators possess an excellent conceptual understanding of the most philosophically interesting physics, relativity and quantum mechanics.

This concentration should prepare a student either for graduate study, especially in a history and philosophy of science (HPS) program, or for employment in science education or journalism. Other professions such as law and medicine will look favorably on such concentrators for having versatile interests and being able to master difficult material. The concentration may serve as an excellent preparation for a law school since physics and philosophy both exercise a rigorous approach to problems of immediate relevance to life but at the same time assume two complimentary and sometimes competing viewpoints.

Advising

Concentration advisors from the Departments of Physics and Philosophy will guide students working towards the A.B. degree.

Curriculum

The curriculum builds around the fields of physics that have had the biggest impact on philosophy, especially Quantum Physics, and the fields of philosophy most relevant for physics, such as Epistemology, Metaphysics and Philosophy of Physics. It is strongly recommended that students complete at least one relevant history course.

There are 11 required courses (5 in Physics, 5 in Philosophy or History, one course in mathematics) and a final project. The choice of the courses is dictated by the following considerations. The field of physics with both deepest philosophical implications and deepest influence on the rest of physics is Quantum Mechanics. Thus, a 1000-level course in Quantum Mechanics or a closely related field such as Statistical Mechanics is indispensable. The second field of physics most relevant for the concentration is Relativity. This field touches upon and serves as a foundation for a broad list of subjects with major philosophical implications of their own, for example: PHYS 1170, PHYS 1280, PHYS 1510, PHYS 1100. This requires another 1000-level physics course in the concentration. 1000-level Physics courses cannot be taken without certain preliminary work, most importantly, PHYS 0470, which serves as a prerequisite for most higher-level physics courses and which relies in turn on PHYS 0160 or PHYS 0060. Another lower-level physics course is necessary for a student to develop familiarity with the tools which have been employed in producing the physics knowledge.

A natural introduction into philosophy of physics comes from a course in Early Modern Philosophy. To a large extent, Early Modern Philosophy was shaped by scholars who combined interest in philosophy and physics (e.g., Rene Descartes, Blaise Pascal, Gottfried Wilhelm Leibniz). The influence of the XVII century physics revolution on other central figures such as Kant is unquestionable. Early Modern Philosophy sets an intellectual stage for many subsequent developments in the Philosophy of Physics and directly addresses some of the most perplexing issues like the connection (or lack thereof) between physics and religion. The core of the Philosophy requirement involves two courses in Epistemology, Metaphysics and Philosophy of Science. One course in this field would not be sufficient due to its very broad nature. Students are strongly advised to take a relevant History course. This requirement can be substituted by an additional philosophy course to reflect interests of those students who want a deeper background in Epistemology, Metaphysics and Philosophy of Science or have other related interests such as Ancient Natural Philosophy.

In addition to the above philosophy courses, PHIL 0210 (Science, Perception, and Reality) serves as a gateway into the concentration. It may be substituted by other relevant courses such as PHYS 0100 (Flat

Earth to Quantum Uncertainty: On the Nature and Meaning of Scientific Explanation).

A course in calculus is a prerequisite for most physics and some philosophy classes.

Required courses for the A.B. degree are listed below:

Physics Courses		
Select one of the following introductory courses in Modern Physics:		1
PHYS 0060	Foundations of Electromagnetism and Modern Physics	
PHYS 0160	Introduction to Relativity, Waves and Quantum Physics	
One course in Special Relativity and Classical Field Theory:		1
PHYS 0470	Electricity and Magnetism	
Select one of the following in Methods of Experimental and Theoretical physics:		1
PHYS 0500	Advanced Classical Mechanics	
PHYS 0560	Experiments in Modern Physics	
Select one of the following in Quantum Mechanics and its applications		1
PHYS 1410	Quantum Mechanics A	
PHYS 1530	Thermodynamics and Statistical Mechanics	
One more 1000-level Physics course		1
Philosophy Courses		
Select one of the following gateway courses:		1
PHIL 0210	Early Modern Philosophy	
PHIL 0060	Modern Science and Human Values	
PHIL 0640	Logic	
Select one of the following courses in Early Modern Philosophy:		1
PHIL 0210	Early Modern Philosophy	
PHIL 1210	Locke, Berkeley, Hume and Others	
PHIL 1220	17th Century Continental Rationalism	
PHIL 1230	Kant: The Critique of Pure Reason	
Select two of the following courses in Epistemology, Metaphysics and Philosophy of Science:		2
PHIL 1705	Epistemology	
PHIL 1735	Metaphysics	
PHIL 1755	Philosophy of Science	
PHIL 1775	Philosophy of Quantum Mechanics	
PHIL 1780	Time	
History Courses		
Select one of the following courses in History of Science: [1]		1
HIST 0522N	Reason, Revolution and Reaction in Europe	
HIST 1825M	Science at the Crossroads	
HIST 1976I	Imperialism and Environmental Change	
Calculus		
Select one of the following:		1
MATH 0180	Multivariable Calculus	
MATH 0200	Multivariable Calculus (Physics/ Engineering)	
MATH 0350	Multivariable Calculus With Theory	
Final Project		
Select one of the following:		1
PHIL 1990	Independent Studies	
PHYS 1990	Senior Conference Course	
A course from the PHIL 0990 Senior Seminar series		
Any graduate seminar in Philosophy		
Total Credits		**12**

[1] Or one more Philosophy course.

Honors

Seniors wishing to earn honors by presenting a senior honors thesis should consult their concentration advisor during their sixth semester or at the start of the seventh semester concerning procedures and requirements. Students may earn honors by presenting a senior thesis judged to be of honors quality by two readers. In addition to completing the usual nonhonors requirements, the student should also have a grade point average of over 3.4 in physics, philosophy and history of science courses (of which at least five must be taken for a letter grade). Honors theses are usually prepared over a period of two semesters with an advisor from the Department of Physics or the Department of Philosophy.

Chemical Physics Concentration Requirements

Chemical Physics is an interdisciplinary field at the crossroads of chemistry and physics and is administered jointly by the two departments. The concentration provides students with a broad-based understanding in fundamental molecular sciences, as well as a background for graduate studies in physical chemistry, chemical physics, or molecular engineering. Concentrators are required to take twenty courses in chemistry, physics, and mathematics, although approved courses in applied mathematics, biology, computer science, geological sciences, or engineering may be substitutes. Chemical Physics concentrators are also advised to take at least six courses in the humanities and social sciences. Chemical Physics concentrators at all levels (first-year through seniors) are actively involved in research with faculty members in both departments.

Standard program for the Sc.B. degree

Twenty-one semester courses[1] in chemistry, physics, and mathematics, with a minimum of four semester courses in mathematics. The expectation is that courses required for a concentration in Chemical Physics will be taken for a letter grade. Core courses are:

CHEM 0330	Equilibrium, Rate, and Structure	1
CHEM 0350	Organic Chemistry I	1
CHEM 0500	Inorganic Chemistry	1
CHEM 1140	Physical Chemistry: Quantum Chemistry	1
PHYS 0070	Analytical Mechanics	1
PHYS 0160	Introduction to Relativity, Waves and Quantum Physics	1
PHYS 0470	Electricity and Magnetism	1
Select one of the following laboratory courses:		1
CHEM 1160	Physical Chemistry Laboratory	
PHYS 0560	Experiments in Modern Physics	
PHYS 1560	Modern Physics Laboratory	
Select one course in statistical mechanics:		1
CHEM 1150	Physical Chemistry: Thermodynamics and Statistical Mechanics	
PHYS 1530	Thermodynamics and Statistical Mechanics	
MATH 0190	Single Variable Calculus, Part II (Physics/ Engineering)	1
MATH 0200	Multivariable Calculus (Physics/ Engineering)	1
MATH 0520	Linear Algebra	1
Seven courses, primarily at the 1000 or 2000 level, in chemistry or physics.		7
Select two semesters of independent study:		2
PHYS 1990	Senior Conference Course	
CHEM 0980	Undergraduate Research	
Total Credits		**21**

[1] Other approved courses in applied mathematics, biology, computer science, geological sciences, or engineering may be substituted for some of the twenty-one.
Students are advised to take at least six courses in the humanities and social sciences.

Requirements for Honors

All Chemical Physics concentrators who have grades of A or S with distinction in a majority of their concentration courses will be considered for Honors; no separate application is necessary.

The requirements for Honors in Chemical Physics are:

* Grades of A or S with distinction in a majority of courses taken for the concentration.

* Two semesters of Independent Study (CHEM 0980 or equivalent. Guidelines and requirements associated with Independent Study are in the Undergraduate Concentration Handbook which can be found at the department website (http://www.brown.edu/academics/chemistry/undergraduate/).

* A Thesis in a form approved and recommended by the research advisor. Additional information about thesis guidelines will be provided to seniors by the Concentration Advisor.

* A Poster presentation at the chemistry department's spring undergraduate poster session.

Engineering and Physics Concentration Requirements

The program is designed to ensure that students take a significant portion of the usual curriculum in Engineering and Physics, obtain substantial laboratory experience, and take several upper-level elective courses, focusing on applied science. Students may take either the standard Physics or Engineering programs during their first and second years and then switch to this combined program. The Sc.B. degree program in Engineering and Physics is not accredited by ABET and is mostly intended to prepare students for graduate study in applied science and engineering. Since the requirements include both quantum mechanics with the physics concentrators and analog electronics with EE concentrators, as well as more mathematics than either Physics or Engineering, it is one of the more demanding programs at Brown.

The following standard program assumes that a student begins mathematics courses at Brown with MATH 0100 or MATH 0190. Students who begin in MATH 0200 can substitute an additional science, engineering or higher-level mathematics course for the MATH 0190 requirement. To accommodate the diverse preparation of individual students, variations of the following sequences and their prerequisites are possible with permission of the appropriate concentration advisor and the instructors involved. We recommend that each student's degree program be submitted for prior approval (typically in semester four) and scrutinized for compliance (in semester seven) by one faculty member from the Department of Physics and one faculty member from the School of Engineering.

Select one of the following two course sequences:		2
ENGN 0040 & ENGN 0030	Engineering Statics and Dynamics and Introduction to Engineering	
or ENGN 0031	Honors Introduction to Engineering	
or ENGN 0032	Introduction to Engineering: Design	
PHYS 0050 & PHYS 0060	Foundations of Mechanics and Foundations of Electromagnetism and Modern Physics	
PHYS 0070 & PHYS 0160	Analytical Mechanics and Introduction to Relativity, Waves and Quantum Physics	
MATH 0190	Single Variable Calculus, Part II (Physics/ Engineering)	1
or MATH 0100	Single Variable Calculus, Part II	
MATH 0200	Multivariable Calculus (Physics/ Engineering)	1
or MATH 0180	Multivariable Calculus	
or MATH 0350	Multivariable Calculus With Theory	
Select three additional higher-level math, applied math, or mathematical physics (PHYS 0720) courses.		3
CSCI 0111	Computing Foundations: Data	1
or APMA 0160	Introduction to Scientific Computing	
or CSCI 0150	Introduction to Object-Oriented Programming and Computer Science	
or CSCI 0170	Computer Science: An Integrated Introduction	
or CSCI 0190	Accelerated Introduction to Computer Science	
ENGN 0510	Electricity and Magnetism	1
or PHYS 0470	Electricity and Magnetism	
ENGN 1690	Photonics Devices and Sensors	1
or PHYS 1510	Advanced Electromagnetic Theory	
PHYS 0500	Advanced Classical Mechanics	1
or ENGN 1370	Advanced Engineering Mechanics	
PHYS 1410	Quantum Mechanics A	1
PHYS 1420	Quantum Mechanics B	1
PHYS 1530	Thermodynamics and Statistical Mechanics	1
or ENGN 0720	Thermodynamics	
ENGN 1620	Analysis and Design of Electronic Circuits	1
CHEM 0330	Equilibrium, Rate, and Structure	1
or ENGN 0310	Mechanics of Solids and Structures	
or ENGN 0810	Fluid Mechanics	
or PHYS 1600	Computational Physics	
ENGN 0410	Materials Science	1
or ENGN 1560	Applications in Microwave Communications	
or PHYS 0560	Experiments in Modern Physics	
PHYS 1560	Modern Physics Laboratory	1
or ENGN 1590	Semiconductor Devices	
or an approved 2000-level engineering or physics course.		
A thesis under the supervision of a physics or engineering faculty member:		1
PHYS 1990	Senior Conference Course	
or ENGN 1970	Independent Studies in Engineering	
or ENGN 1971	Independent Study in Engineering	
or ENGN 1972	Independent Study in Engineering Design	
or ENGN 1973	Independent Study in Engineering Design	
* Students are also encouraged to take courses dealing with the philosophical, ethical, or political aspects of science and technology.		
Total Credits		**19**

Professional Track

The requirements for all undergraduate professional tracks within concentrations are standardized and additional information can be found here:

https://bulletin.brown.edu/undergradproftrack/

Astronomy Concentration Requirements

Along with Greek, Latin, and Mathematics, Astronomy counts as one of the oldest continuously taught subjects in the Brown curriculum. It is the study of the properties of stars, galaxies, and the Universe, and as such combines elements from the disciplines of both Physics and Planetary Geology. Students pursuing this concentration complete introductory coursework in classical mechanics, relativity, and astrophysics, along with mathematics and elecromagnetism. They go on to complete courses

in stellar and extragalactic astrophysics as well as cosmology. Facilities available to concentrators include the historic Ladd Observatory.

Standard concentration for the A.B. degree

Eleven or twelve courses are required (depending on the satisfaction of prerequisites).

Prerequisites		
PHYS 0070	Analytical Mechanics	1
PHYS 0160	Introduction to Relativity, Waves and Quantum Physics [1]	1
PHYS 0270	Astronomy and Astrophysics	1
Select one of the following Series:		1-2
MATH 0170 & MATH 0180	Single Variable Calculus, Part II (Accelerated) and Multivariable Calculus	
MATH 0190 & MATH 0200	Single Variable Calculus, Part II (Physics/ Engineering) and Multivariable Calculus (Physics/ Engineering)	
MATH 0350	Multivariable Calculus With Theory (or equivalent)	
PHYS 0470	Electricity and Magnetism	1
Program		
Select one of the following mathematics courses:		1
MATH 0520	Linear Algebra	
MATH 0540	Linear Algebra With Theory	
PHYS 0720	Methods of Mathematical Physics	
APMA 0330	Methods of Applied Mathematics I	
APMA 0340	Methods of Applied Mathematics II	
Select two of the following astrophysics courses:		2
PHYS 1100	General Relativity	
PHYS 1250	Stellar Structure and the Interstellar Medium	
PHYS 1270	Extragalactic Astronomy and High-Energy Astrophysics	
PHYS 1280	Introduction to Cosmology	
Three additional 1000- or 2000-level courses in physics or a related field, suggestions:		3
APMA 1670	Statistical Analysis of Time Series	
EEPS 0810	Planetary Geology	
EEPS 1710	Remote Sensing of Earth and Planetary Surfaces	
EEPS 1810	Physics of Planetary Evolution	
ENGN 1860	Advanced Fluid Mechanics	
MATH 1060	Differential Geometry	
PHYS 0500	Advanced Classical Mechanics	
PHYS 0560	Experiments in Modern Physics	
PHYS 1410	Quantum Mechanics A	
PHYS 1510	Advanced Electromagnetic Theory	
PHYS 1530	Thermodynamics and Statistical Mechanics	
PHYS 1560	Modern Physics Laboratory	
Total Credits		**11-12**

[1] PHYS 0050 and PHYS 0060 can be taken in lieu of PHYS 0160

Physics Graduate Program

The Department of Physics offers graduate programs leading to the Master of Science (ScM) degree and the Doctor of Philosophy (PhD) Degree. For more information on admission and program requirements, please visit the following website: ~~http://www.brown.edu/academics/gradschool/programs/physics~~

Master of Science (ScM)

The Sc.M. degree recognizes a significant level of academic achievement beyond an undergraduate degree. A total of 8 credits in 2000-level courses form the main requirement for the Sc.M. degree in Physics. Of the eight required courses, four will be selected from the six core courses of the Ph.D. program (PHYS 2010, 1720 or 2020**, 2040, 2050, 2060, 2140). Four additional credits at the 2000 level are required. These courses are to be selected from the remaining core courses or the large number of other upper-level Physics courses. With pre-approval of the DMP, up to two of these additional credits, also at the 2000 level, can be taken in another department. Preparation of a Master's thesis is recommended, as it forms an important pillar of professional training.

***Please note: 2030 can be taken instead of 1720 or 2020 if the student has passed the entrance exam.*

Students with less rigorous physics backgrounds will be advised to take a mixture of 1000-level and 2000-level courses during their course of study, necessitating a 3- or 4-semester track to completion.

Course selection and registration for recently admitted students are held in September after a faculty advising session during orientation. Registration remains open for the first two weeks as a 'shopping period' during which students can make final course decisions.

Core Courses

PHYS 2010	Techniques in Experimental Physics
PHYS 2030	Classical Theoretical Physics I
PHYS 2040	Classical Theoretical Physics II
PHYS 2050	Quantum Mechanics
PHYS 2060	Quantum Mechanics
PHYS 2140	Statistical Mechanics

Four additional credits at the 2000 level are required. These courses are to be selected from the remaining core courses or the large number of other upper level physics courses. Up to two of these can be taken in research, or taken in another department with prior approval of the program director.

PHYS 2020	Mathematical Methods of Engineers and Physicists
PHYS 2070	Advanced Quantum Mechanics
PHYS 2170	Introduction to Nuclear and High Energy Physics
PHYS 2280	Astrophysics and Cosmology
PHYS 2300	Quantum Theory of Fields I
PHYS 2320	Quantum Theory of Fields II
PHYS 2340	Group Theory
PHYS 2410	Solid State Physics I
PHYS 2420	Solid State Physics II
PHYS 2430	Quantum Many Body Theory
PHYS 2470	Advanced Statistical Mechanics
PHYS 2600	Computational Physics
PHYS 2620H	Quantum Computation, Information, and Sensing
PHYS 2620J	Statistical Physics in Inference and (Deep) Learning
PHYS 2980	Research in Physics
or PHYS 2981	Research in Physics

Doctor of Philosophy (PhD)

Core Courses:

PHYS 2010	Techniques in Experimental Physics
PHYS 2030	Classical Theoretical Physics I
PHYS 2040	Classical Theoretical Physics II
PHYS 2050	Quantum Mechanics
PHYS 2060	Quantum Mechanics
PHYS 2140	Statistical Mechanics

Beyond the core courses, PhD candidates are expected to pass four additional advanced courses. At least one of the courses must fall outside the student's research area. These courses are to be selected from the following:

PHYS 2020	Mathematical Methods of Engineers and Physicists
PHYS 2070	Advanced Quantum Mechanics
PHYS 2100	General Relativity
PHYS 2170	Introduction to Nuclear and High Energy Physics
PHYS 2280	Astrophysics and Cosmology
PHYS 2300	Quantum Theory of Fields I
PHYS 2320	Quantum Theory of Fields II
PHYS 2340	Group Theory
PHYS 2410	Solid State Physics I
PHYS 2420	Solid State Physics II
PHYS 2430	Quantum Many Body Theory
PHYS 2470	Advanced Statistical Mechanics
PHYS 2600	Computational Physics
PHYS 2630	Biological Physics

Courses

PHYS 0030. Basic Physics A.
Survey of mechanics for concentrators in sciences other than physics-including premedical and life science students. Students with more advanced math training are advised to take PHYS 0050, which covers the same topics in physics. Lectures and laboratory. Six hours of attendance.

Fall	PHYS0030	S01	10309	MWF	11:00-11:50(16)	'To Be Arranged'
Fall	PHYS0030	S02	10310	MWF	12:00-12:50(15)	'To Be Arranged'
Fall	PHYS0030	L01	17256	T	8:30-10:20	'To Be Arranged'
Fall	PHYS0030	L02	17257	T	12:30-2:20	'To Be Arranged'
Fall	PHYS0030	L03	17258	T	2:30-4:20	'To Be Arranged'
Fall	PHYS0030	L04	17259	W	9:00-10:50	'To Be Arranged'
Fall	PHYS0030	L05	17260	W	1:00-2:50	'To Be Arranged'
Fall	PHYS0030	L06	17261	W	5:00-4:50	'To Be Arranged'
Fall	PHYS0030	L07	17262	Th	8:30-10:20	'To Be Arranged'
Fall	PHYS0030	L08	17263	Th	12:30-2:20	'To Be Arranged'
Fall	PHYS0030	L09	17264	Th	2:30-4:00	'To Be Arranged'
Fall	PHYS0030	L10	17265	F	9:00-10:50	'To Be Arranged'
Fall	PHYS0030	L11	17266	F	1:00-2:50	'To Be Arranged'
Fall	PHYS0030	L12	17267	Arranged		'To Be Arranged'
Spr	PHYS0030	S01	20278	MWF	1:00-1:50(06)	'To Be Arranged'
Spr	PHYS0030	L01	25656	T	12:30-2:20	'To Be Arranged'
Spr	PHYS0030	L02	25657	T	2:30-4:20	'To Be Arranged'
Spr	PHYS0030	L03	25658	W	9:00-10:50	'To Be Arranged'

PHYS 0040. Basic Physics B.
Survey of electricity, magnetism, optics, and modern physics for concentrators in sciences other than physics-including premedical students or students without prior exposure to physics who require a less rigorous course than PHYS 0050, 0060. Lectures, conferences, and laboratory.

Fall	PHYS0040	S01	10311	MWF	12:00-12:50(15)	'To Be Arranged'
Fall	PHYS0040	L01	17268	T	12:30-2:20	'To Be Arranged'
Fall	PHYS0040	L02	17269	W	9:00-10:50	'To Be Arranged'
Fall	PHYS0040	L03	17270	W	1:00-2:50	'To Be Arranged'
Spr	PHYS0040	S01	20279	MWF	11:00-11:50(04)	'To Be Arranged'
Spr	PHYS0040	S02	20280	MWF	12:00-12:50(01)	'To Be Arranged'
Spr	PHYS0040	L01	25659	T	8:30-10:20	'To Be Arranged'
Spr	PHYS0040	L02	25660	T	12:30-2:20	'To Be Arranged'
Spr	PHYS0040	L03	25661	T	2:30-4:20	'To Be Arranged'
Spr	PHYS0040	L04	25662	W	9:00-10:50	'To Be Arranged'
Spr	PHYS0040	L05	25663	W	1:00-2:50	'To Be Arranged'
Spr	PHYS0040	L06	25664	W	3:00-4:50	'To Be Arranged'
Spr	PHYS0040	L07	25665	Th	8:30-10:20	'To Be Arranged'
Spr	PHYS0040	L08	25666	Th	12:30-2:20	'To Be Arranged'
Spr	PHYS0040	L09	25667	Th	2:30-4:20	'To Be Arranged'
Spr	PHYS0040	L10	25668	F	9:00-10:50	'To Be Arranged'
Spr	PHYS0040	L11	25669	F	1:00-2:50	'To Be Arranged'
Spr	PHYS0040	L12	25670	Arranged		'To Be Arranged'

PHYS 0050. Foundations of Mechanics.
An introduction to Newtonian mechanics that employs elementary calculus. Intended for science concentrators. Potential physics concentrators, who do not have adequate preparation for PHYS 0070, may enroll, but are urged to continue with PHYS 0160 rather than PHYS 0060. Lectures, conferences and laboratory. Six hours of attendance. Recommended: MATH 0090 or MATH 0100.

Fall	PHYS0050	S01	10312	MW	8:30-9:50(09)	'To Be Arranged'
Fall	PHYS0050	L01	17271	T	12:30-2:20	'To Be Arranged'
Fall	PHYS0050	L02	17272	T	2:30-4:20	'To Be Arranged'
Fall	PHYS0050	L03	17273	W	1:00-2:50	'To Be Arranged'
Fall	PHYS0050	L04	17274	W	3:00-4:50	'To Be Arranged'
Fall	PHYS0050	L05	17275	Th	12:30-2:20	'To Be Arranged'
Fall	PHYS0050	L06	17276	Th	2:30-4:20	'To Be Arranged'
Fall	PHYS0050	L07	17277	Arranged		'To Be Arranged'

PHYS 0060. Foundations of Electromagnetism and Modern Physics.
An introduction to the principles and phenomena of electricity, magnetism, optics, and the concepts of modern physics. Recommended for those who wish to limit their college physics to two semesters but seek a firm grounding in the subject, including but not limited to those with some previous knowledge of physics. Lectures, conferences, and laboratory. Six hours of attendance. Prerequisite: PHYS 0050. Recommended: MATH 0100.

Spr	PHYS0060	S01	20281	MW	8:30-9:50(02)	'To Be Arranged'
Spr	PHYS0060	L01	25672	T	12:30-2:20	'To Be Arranged'
Spr	PHYS0060	L02	25673	T	2:30-4:20	'To Be Arranged'
Spr	PHYS0060	L03	25674	W	1:00-2:50	'To Be Arranged'
Spr	PHYS0060	L04	25675	W	3:00-4:50	'To Be Arranged'
Spr	PHYS0060	L05	25676	Th	12:30-2:20	'To Be Arranged'
Spr	PHYS0060	L06	25677	Th	2:30-4:20	'To Be Arranged'
Spr	PHYS0060	L07	25678	Arranged		'To Be Arranged'

PHYS 0070. Analytical Mechanics.
A mathematically more rigorous introduction to Newtonian mechanics than PHYS 0050. For first-year students and sophomores who have studied physics previously and have completed a year of calculus. Lectures, conferences, and laboratory. Six hours of attendance. Prerequisites: high school physics and calculus or written permission. S/NC

Fall	PHYS0070	S01	10313	MWF	9:00-9:50(09)	'To Be Arranged'
Fall	PHYS0070	L01	17278	T	12:30-2:20	'To Be Arranged'
Fall	PHYS0070	L02	17279	T	2:30-4:20	'To Be Arranged'
Fall	PHYS0070	L03	17280	W	1:00-2:50	'To Be Arranged'
Fall	PHYS0070	L04	17281	W	3:00-4:50	'To Be Arranged'
Fall	PHYS0070	L05	17282	Th	12:30-2:20	'To Be Arranged'
Fall	PHYS0070	L06	17283	Th	2:30-4:20	'To Be Arranged'
Fall	PHYS0070	L07	17284	Arranged		'To Be Arranged'

PHYS 0100. Flat Earth to Quantum Uncertainty: On the Nature and Meaning of Scientific Explanation.
Physics has had a dramatic impact on our conception of the universe, our ideas concerning the nature of knowledge, and our view of ourselves. Philosophy, sometimes inspired by developments in physics, considers the impact of such developments on our lives. In this seminar, students will explore how classical and modern physical theory have affected our view of the cosmos, of ourselves as human beings, as well as our view of the relation of mathematical or physical structures to 'truth' or 'reality.' Through a study of physics as well as selected philosophical readings, we will consider how we can know anything, from seemingly simple facts to whether a machine is conscious. Enrollment limited to 19 first year students. Instructor permission required.

PHYS 0110. Excursion to Biophysics.
This new course aims at freshmen with good preparation in high school physics, chemistry and biology, but who have not had a set mind what specific disciplines to focus on in their college study at Brown. The course will introduce important physics concepts and techniques relevant to biology and medicine, such as diffusion and transport of molecules and intracellular components, Brown motion and active swimming of microbes, motion of particles confined by a harmonic potential, Boltzmann distribution, exponential growth or decay, and statistics of single molecule behavior. The goal of the course is to cultivate interest and provide essential basics for more rigorous study of biological physics as a branch of interdisciplinary science. Enrollment limited to 19 first year students. Instructor permission required.

PHYS 0111. Are There Extra Dimensions Under Your Bed?.
Discusses some of the most exciting questions confronting contemporary physical science in a fashion suitable for both humanists and scientists. What are particles, antiparticles, superstrings, and black holes? How are space and time related? How are mass and gravity related to space and time? Do we live in a three-dimensional world, or are there extra dimensions? The seminar will address such questions with conceptual explanations based upon current research on campus, and highlight the experiments at the energy frontier, being carried out by the world's largest scientific instrument to-date, the Large Hadron Collider, located in Geneva, Switzerland. Enrollment limited to 19 first year students.

PHYS 0112. Extra-Solar Planets and the Search for Extraterrestrial Life.
The course will cover the significant developments in the detection and characterization of extra-solar planetary systems in the past almost 30 years. We will study the techniques for detecting planets outside of our solar system, the properties of the exoplanets discovered so far, and the prospects for future discoveries, with an emphasis on the search for "Earth-analogues" and the implications for astrobiology.

PHYS 0113. Squishy Physics.
A freshman seminar to explore everyday applications of physics. It offers practical training on project based learning. The course involves hands-on experimentation, data analysis and presentation. The course is designed for students interested in any field of science with no pre-requisite. The topics covered include motion, forces, flow, elasticity, polymers, gels, electricity, energy, etc. Students will be guided to work on several projects over the semester. They are required to report their projects in both written and oral reports. There is no exam for the course. Students are required to register for one of the labs.

PHYS 0114. The Science and Technology of Energy.
Energy plays fundamental roles in society. Its use underlies improvements in the living standard; the consequences of its use are having a significant impact on the Earth's climate; its scarcity in certain forms is a source of insecurity and political conflict. This course will introduce the fundamental laws that govern energy and its use. Physical concepts to be covered: mechanical energy, thermodynamics, the Carnot cycle, electricity and magnetism, quantum mechanics, and nuclear physics. Technological applications include wind, hydro, and geothermal energy, engines and fuels, electrical energy transmission and storage, solar energy and photovoltaics, nuclear reactors, and biomass. Enrollment limited 19.

PHYS 0120. Adventures in Nanoworld.
Richard Feynman famously said, "There's plenty of room at the bottom," about the possibility of building molecular-size machines operating according to Quantum Mechanics. Scientists are now learning the art, and students in this course will use basic physics and simple mathematical models to understand the phenomena and materials in the nanoworld. Non-science concentrators and potential science concentrators alike will learn about important classes of nanosystems such as macromolecules, nanotubes, quantum dots, quantum wires, and films. We will learn how people make nanosystems and characterize them. We will consider existing and potential applications of nanotechnology, including molecular motors, nanoelectronics, spintronics, and quantum information. Enrollment limited to 19 first year students.

PHYS 0121. Introduction to Environmental Physics: The Quantum Mechanics of Global Warming.
We will use basic physics and simple mathematical models to investigate climate change, energy and entropy, the dispersal of pollutants, solar power, and other aspects of environmental science. Lectures will be supplemented with demonstrations of key physical principles. Emphasis will be placed on quantitative reasoning.

PHYS 0150. The Jazz of Modern Physics.
This course, aimed at both students in the humanities and sciences, will explore the myriad surprising ways that jazz music is connected to modern physics. No background in physics, mathematics or music is required, as all of these foundational concepts and tools will be introduced.
The Jazz of Physics has three interconnected components:
(1) Using concepts and analogies from music and acoustics to explore the key conceptual ideas in modern physics such as quantum mechanics/ information, general relativity, particle physics, dark energy and big bang cosmology.
(2) Exploring the parallels between jazz and physics through the lens of 20th century physics and jazz history, as well as key innovations in both fields with an eye towards future innovations.
(3) Students will learn the tools of signification in physics and develop group projects with a final product.
The course will consist of lectures, related homework sets, weekly discussion meetings, and a final study where groups of students will select a topic of interest.

PHYS 0160. Introduction to Relativity, Waves and Quantum Physics.
A mathematically rigorous introduction to special relativity and quantum mechanics. The second course in the three-semester sequence (PHYS 0470 being the third) for those seeking the strongest foundation in physics. Also suitable for students better served by an introduction to modern physics rather than electromagnetism. Lectures, conferences, and laboratory. Six hours of attendance. Prerequisite: PHYS 0070 or 0050. Recommended: MATH 0180 or 0200. S/NC

Spr	PHYS0160	S01	20282	MWF	9:00-9:50(02)	'To Be Arranged'
Spr	PHYS0160	L01	25679	T	12:30-2:20	'To Be Arranged'
Spr	PHYS0160	L02	25680	T	2:30-4:20	'To Be Arranged'
Spr	PHYS0160	L03	25681	W	1:00-2:50	'To Be Arranged'
Spr	PHYS0160	L04	25682	W	3:00-4:50	'To Be Arranged'
Spr	PHYS0160	L05	25683	Th	12:30-2:20	'To Be Arranged'
Spr	PHYS0160	L06	25684	Th	2:30-4:20	'To Be Arranged'
Spr	PHYS0160	L07	25685	Arranged		'To Be Arranged'

PHYS 0180. Physics for Non-Physicists: An Introduction to Classical and Modern Physics.
This course is an introduction to many major concepts in physics. It is intended for a general audience, and calculus is not required. Along the way, we will address the question “what goes into making a scientific theory?” using the works of Euclid, Galileo, Newton and others as examples. Concepts range historically from planetary motion (addressed at least as early as Ancient Greece) to modern physics topics that are still under debate today. These concepts include (but are not limited to) motion, forces, energy, electricity and magnetism, special relativity and quantum mechanics.

PHYS 0220. Astronomy.
An introduction to basic ideas and observations in astronomy, starting with the observed sky, coordinates and astronomical calendars and cycles, the historical development of our understanding of astronomical objects. Particular emphasis is placed on the properties of stars, galaxies, and the Universe as a whole, including the basic ideas of cosmology. The material is covered at a more basic level than PHYS 0270. Knowledge of basic algebra and trigonometry is required, but no experience with calculus is necessary. The course includes evening laboratory sessions.

Spr	PHYS0220	S01	20283	TTh	10:30-11:50(09)	'To Be Arranged'

PHYS 0270. Astronomy and Astrophysics.
A complete survey of basic astronomy, more rigorous than is offered in PHYS 0220. Requires competence in algebra, geometry, trigonometry, and vectors and also some understanding of calculus and classical mechanics. Laboratory work required. This course or an equivalent required for students concentrating in astronomy. The course includes conferences and evening laboratory sessions.

Fall	PHYS0270	S01	10314	TTh	1:00-2:20(06)	'To Be Arranged'

PHYS 0470. Electricity and Magnetism.
Electric and magnetic fields. Motion of charged particles in fields. Electric and magnetic properties of matter. Direct and alternating currents. Maxwell's equations. Laboratory work. Prerequisites: PHYS 0040, 0060, or 0160; and MATH 0180, 0200 or 0350. Labs meet every other week.

Fall	PHYS0470	S01	10315	MWF	10:00-10:50(14)	'To Be Arranged'
Fall	PHYS0470	L01	17285	T	9:00-11:50	'To Be Arranged'
Fall	PHYS0470	L02	17286	T	2:30-5:20	'To Be Arranged'
Fall	PHYS0470	L03	17287	W	2:00-4:50	'To Be Arranged'
Fall	PHYS0470	L04	17288	Th	9:00-11:50	'To Be Arranged'
Fall	PHYS0470	L05	17289	Th	2:30-5:20	'To Be Arranged'
Fall	PHYS0470	L06	17290	F	1:00-3:50	'To Be Arranged'

PHYS 0500. Advanced Classical Mechanics.
Dynamics of particles, rigid bodies, and elastic continua. Normal modes. Lagrangian and Hamiltonian formulations. Prerequisites: PHYS 0070, 0160 or 0050, 0060 and MATH 0180 or 0200; or approved equivalents.

Spr	PHYS0500	S01	20284	MWF	10:00-10:50(03)	'To Be Arranged'

PHYS 0560. Experiments in Modern Physics.
Introduction to experimental physics. Students perform fundamental experiments in modern quantum physics, including atomic physics, nuclear and particle physics, and condensed matter physics. Visits to research labs at Brown acquaint students with fields of current research. Emphasizes laboratory techniques, statistics, and data analysis. Three lecture/discussion hours and three laboratory hours each week. Required of all physics concentrators. Prerequisites: PHYS 0070, 0160 or 0050, 0060; 0470.

Spr	PHYS0560	S01	20285	MWF	11:00-11:50(04)	'To Be Arranged'
Spr	PHYS0560	L01	25686	T	9:00-11:50	'To Be Arranged'
Spr	PHYS0560	L02	25687	W	2:00-4:50	'To Be Arranged'
Spr	PHYS0560	L03	25688	Th	2:30-5:20	'To Be Arranged'
Spr	PHYS0560	L04	25689	F	2:00-4:50	'To Be Arranged'
Spr	PHYS0560	L05	25690	T	2:30-5:20	'To Be Arranged'

PHYS 0720. Methods of Mathematical Physics.
This course is designed for sophomores in physical sciences, especially those intending to take sophomore or higher level Physics courses. Topics include linear algebra (including linear vector spaces), Fourier analysis, ordinary and partial differential equations, complex analysis (including contour integration). Pre-requisites: PHYS 0060 or 0160, MATH 0180, 0200 or 0350, or consent of the instructor.

Fall	PHYS0720	S01	10316	TTh	1:00-2:20(06)	'To Be Arranged'

PHYS 0790. Physics of Matter.
An introduction to the principles of quantum mechanics and their use in the description of the electronic, thermal, and optical properties of materials. Primarily intended as an advanced science course in the engineering curriculum. Open to others by permission. Prerequisites: ENGN 0040, APMA 0340 or equivalents.

Fall	PHYS0790	S01	10318	TTh	9:00-10:20(05)	'To Be Arranged'

PHYS 1100. General Relativity.
An introduction to Einstein's theory of gravity, including special relativity, spacetime curvature, cosmology and black holes. Prerequisites: PHYS 0500 and MATH 0520 or MATH 0540 or equivalent, or permission of the instructor. Recommended: PHYS 0720. Offered every other year.

Spr	PHYS1100	S01	20286	TTh	9:00-10:20(05)	'To Be Arranged'

PHYS 1170. Introduction to Nuclear and High Energy Physics.
A study of modern nuclear and particle physics, with emphasis on the theory and interpretation of experimental results. Prerequisites: PHYS 1410, 1420 (may be taken concurrently), or instructor permission.

Spr	PHYS1170	S01	20288	MWF	12:00-12:50(01)	'To Be Arranged'

PHYS 1250. Stellar Structure and the Interstellar Medium.
This class is an introduction to the physics of stars and their environment. The course covers the fundamental physics that set the physical properties of stars, such as their luminosity, size, spectral properties and how these quantities evolve with time. In addition, it includes a study of the physics that takes place in the gaseous environment surrounding stars, the InterStellar Medium (ISM). The ISM is very important because it contains a wealth of information on the evolutionary history of galaxies, their composition, formation and future. Prerequisites: PHYS 0270, PHYS 0470, or instructor permission. PHYS 1530 (perhaps taken concurrently) is strongly recommended but not required.

Spr	PHYS1250	S01	20289	MWF	1:00-1:50(06)	'To Be Arranged'

PHYS 1270. Extragalactic Astronomy and High-Energy Astrophysics.
This course provides an introduction to the astrophysics of galaxies, their structure and evolution, with an emphasis on physical introduction of the observations. Underlying physics concepts such as radiative transfer, nuclear reactions and accretion physics will be introduced. Intended for students at the junior level. Prerequisites: PHYS 0270 and PHYS 0470, and either MATH 0190 or MATH 0200, or instructor permission.

Fall	PHYS1270	S01	10319	MWF	2:00-2:50(01)	'To Be Arranged'

PHYS 1280. Introduction to Cosmology.
The course presents an introduction to the study of the origin, evolution and contents of the Universe. Topics include the expansion of the Universe, relativistic cosmologies, thermal evolution, primordial nucleosynthesis, structure formation and the Cosmic Microwave Background. Prerequisites: PHYS 0160, MATH 0190, MATH 0200, or MATH 0350, or instructor permission.

PHYS 1410. Quantum Mechanics A.
A unified treatment of quanta, photons, electrons, atoms, molecules, matter, nuclei, and particles. Quantum mechanics developed at the start and used to link and explain both the older and newer experimental phenomena of modern physics. Prerequisites: PHYS 0500 and 0560; and MATH 0520, 0540 or PHYS 0720; or approved equivalents.

Fall	PHYS1410	S01	10320	MWF	9:00-9:50(09)	'To Be Arranged'

PHYS 1420. Quantum Mechanics B.
See Quantum Mechanics A, (PHYS 1410) for course description.

Spr	PHYS1420	S01	20290	MWF	9:00-9:50(02)	'To Be Arranged'

PHYS 1510. Advanced Electromagnetic Theory.
Maxwell's laws and electromagnetic theory. Electromagnetic waves and radiation. Special relativity. Prerequisites: PHYS 0470; and MATH 0180, 0200, or 0350; or approved equivalents.

Fall	PHYS1510	S01	10321	TTh	9:00-10:20(05)	'To Be Arranged'

PHYS 1530. Thermodynamics and Statistical Mechanics.
The laws of thermodynamics and heat transfer. Atomic interpretation in terms of kinetic theory and elementary statistical mechanics. Applications to physical problems. Prerequisites: MATH 0180 or 0200 or 0350. Corequisite: PHYS 1410.

Fall	PHYS1530	S01	10322	MWF	10:00-10:50(14)	'To Be Arranged'

PHYS 1560. Modern Physics Laboratory.
A sequence of intensive, advanced experiments often introducing sophisticated techniques. Prerequisites: PHYS 0470, 0500 and 0560; and MATH 0520, 0540 or PHYS 0720; or approved equivalents.

Spr	PHYS1560	S01	20292	TTh	9:00-10:20(05)	'To Be Arranged'

PHYS 1590. Semiconductor Devices.
An introduction to semiconductor device physics and basic electronic properties of semiconductors, including junctions, heterojunction, and fundamental device building blocks. Current and proposed semiconductor devices: field effect transistors, bipolar transistors, quantum-effect devices, and optoelectronic devices. A brief fabrication lab will introduce junction fabrication in the cleanroom. Advanced topics, such as heterojunction bipolar transistors and silicon-on-insulator FETs, are included in the graduate version.

Spr	PHYS1590	S01	26217	MWF	12:00-12:50(01)	(A. Zaslavsky)

PHYS 1600. Computational Physics.
This course provides students with an introduction to scientific computation, primarily as applied to physical science problems. It will assume a basic knowledge of programming and will focus on how computational methods can be used to study physical systems complementing experimental and theoretical techniques. Prerequisites: PHYS 0070, 0160 (or 0050, 0060) and 0470 (or ENGN 0510); MATH 0180 or 0200 or 0350; the ability to write a simple computer program in Fortran, Matlab, C or C++.

Spr	PHYS1600	S01	20302	TTh	1:00-2:20(08)	'To Be Arranged'

PHYS 1610. Biological Physics.
Introduction on structures of proteins, nucleotides, and membranes; electrostatics and hydration; chemical equilibrium; binding affinity and kinetics; hydrodynamics and transport; cellular mechanics and motions; biophysical techniques including sedimentation, electrophoresis, microscopy and spectroscopy. Suitable for undergraduate science and engineering majors and graduate students with limited background in life science. Prerequisites: MATH 0180.

Fall	PHYS1610	S01	10323	TTh	2:30-3:50(12)	'To Be Arranged'

PHYS 1720. Methods of Mathematical Physics.
Designed primarily for sophmore students in physical sciences. Basic elements of and practical examples in linear algebra, the solution of ordinary and Partial Differential Equation, Complex Analysis and Application to Contour Integrals. Intended to prepare students for the mathematics encountered in PHYS 0500, 1410, 1420, 1510 and 1530. Pre-requisites: PHYS 0060 or 0160, MATH 0180, 0200 or 0350, or consent of the instructor.

Fall	PHYS1720	S01	10317	TTh	1:00-2:20(06)	'To Be Arranged'

PHYS 1790. Quantum Optics.
An introduction to the fundamental theory, mathematical formalism, and applications of quantum optics, the study of light and its interactions with matter at microscopic scales. Topics will include: an introduction to quantum mechanics using the bra-ket (or Dirac) notation, quantization of the electromagnetic fields, generation and detection of single photons, non-classical quantum states (single-mode states, Fock or number states, coherent and squeezed states), phasor diagrams, number-phase uncertainty, quantum theory of photoionization/photodetection, quantum description of mirrors, beam splitters, Mach-Zehnder interferometers, spontaneous emission and parametric downconversion, as well as interaction-free measurements. The course is intended for graduate and senior undergraduate students who would like to understand more advanced concepts in emerging fields, such as quantum computing. The material is self-contained, therefore students who do not have a deep background in quantum mechanics or optics will also be able to take the course proficiently

Spr	PHYS1790	S01	20293	M	3:00-5:30(13)	(D. Pacifici)

PHYS 1840. Group Research Project.
No description available.

PHYS 1931S. Medical Physics.
Medical Physics is an applied branch of physics concerned with the application of the concepts and methods to the diagnosis and treatment of human disease. It allies with medical electronics, bioengineering, health physics. Students will familiarize with major texts and literature of medical physics and are exposed to imaging and treatment techniques and quality control procedures. Students will acquire physical and scientific background to pose questions and solve problems in medical physics. Topics include: Imaging -imaging metrics, ionizing radiation, radiation safety, radioactivity, computed tomography, nuclear medicine, ultrasound, magnetic resonance imaging, and Radiation Therapy -delivery systems, treatment planning, brachytherapy, image guidance.

PHYS 1970A. Stellar Physics and the Interstellar Medium.
No description available.

PHYS 1970B. Topics in Optics.
Introduction to optical principles and techniques. Offered to students who have a foundation in physics and are especially interested in optics. The course covers the interaction of light with matter, geometric and wave optics, polarization, fluorescence, and optical instruments (e.g. interferometer, spectrometer, microscope and telescope). Recommended are one physics course (PHYS 0040, PHYS 0060, or ENGN 0040) and one calculus course (MATH 0180, MATH 0200, or MATH 0350), or per instructor's permission.

PHYS 1970C. String Theory for Undergraduates.
This course will concentrate on String Theory. It will be given at introductory/intermediate level with some review of the background material. Topics covered will include dynamical systems, symmetries and Noether’s Theorem; nonrelativistic strings; relativistic systems (particle and string); quantization, gauge fixing, Feynman’s sum over paths; electrostatic analogy; string in curved space-time; and supersymmetry. Some advanced topics will also be addressed, i.e., D-Branes and M-Theory. Recommended prerequisites: PHYS 0470 and 0500, or 0160.

PHYS 1970D. Statistical Physics in Inference and (Deep) Learning.
In this course students will explore the statistical physics principles underlying probabilistic inference and various neural network architectures. The course is designed to bridge the gap between teaching approaches to modern statistical physics that are either purely theoretical, or focus largely on its applications in data analysis. To that end, there will be a conscious effort to study topics such as: MaxEnt principle, variational methods, Hebb's rule, bias-variance tradeoff, regularization, and others with analytical derivations as well as worked-out code examples in Jupyter notebooks. The course will also provide a space for students to interrogate and reflect on the ethical, political, and policy frameworks that are urgently needed in the age of deep learning.

PHYS 1970F. Quantum Information.
Quantum information is the modern study of how to encode and transmit information on the quantum scale--in many ways fundamentally different from classical information. This course will connect a standard treatment of Quantum mechanics with information theory. Some topics will overlap with phys 1410, but information will be presented from a different viewpoint and with new applications. Topics covered will include: measurement, quantum states, bits, density of states, entanglement, quantum information processing, computing, and some special topics. Students will be expected to complete an end of term project for successfull completion of the course.

Spr	PHYS1970F	S01	26126	MWF	2:00-2:50(07)	(A. Rosuel)

PHYS 1970G. Topological Matter.
Topology is a study of the robust properties of geometry, the global stuff that survives wiggles. Topological matter is matter that possesses robust properties that can survive a bit of crud, to the delight of its discoverers. It has breathed new life into topics that have been in textbooks for 75 years. Topics covered include Band Theory, Berry Phase, Topological Insulators, and the Quantum Hall Effect.

PHYS 1970J. Introduction to Fluids.
An introduction to fluids from the perspective of a physicist, this course will use discussion-based, small-group, and interactive pedagogy to explore and learn fundamental aspects of fluids: ideal, viscid, and planetary flows as well as turbulence, boundary layers, and waves. Student preference and feedback will be a major component in determining the topics to be covered as well as how class time is spent. This is recommended as an advanced undergraduate course for Physics majors who have completed their core coursework.

PHYS 1980. Undergraduate Research in Physics.
Designed for undergraduates to participate, individually or in small groups, in research projects mentored by the physics faculty. Students must have taken one year of college level physics. An average of 8 to 10 hours per week of guided research is required as are weekly meetings with the supervising faculty member. Students should consult with faculty to find a mutually agreeable research project and obtain permission to enroll. Section number varies by instructor (students must register for the appropriate section).

PHYS 1990. Senior Conference Course.
Preparation of thesis project. Required of candidates for the degree of bachelor of science with a concentration in physics. Section numbers vary by instructor. Please check Banner for the correct section number and CRN to use when registering for this course.

PHYS 2010. Techniques in Experimental Physics.
No description available.

Fall	PHYS2010	S01	10325	TTh	10:30-11:50(13)	'To Be Arranged'
Spr	PHYS2010	S01	20295	TTh	10:30-11:50(09)	'To Be Arranged'

PHYS 2020. Mathematical Methods of Engineers and Physicists.
An introduction to methods of mathematical analysis in physical science and engineering. The first semester course includes linear algebra and tensor analysis; analytic functions of a complex variable; integration in the complex plane; potential theory. The second semester course includes probability theory; eigenvalue problems; calculus of variations and extremum principles; wave propagation; other partial differential equations of evolution.

Fall	PHYS2020	S01	10326	TTh	10:30-11:50(13)	'To Be Arranged'

PHYS 2030. Classical Theoretical Physics I.
No description available.

Fall	PHYS2030	S01	10327	TTh	9:00-10:20(05)	'To Be Arranged'

PHYS 2040. Classical Theoretical Physics II.
No description available.

Spr	PHYS2040	S01	20296	MWF	10:00-10:50(03)	'To Be Arranged'

PHYS 2050. Quantum Mechanics.
No description available.

Fall	PHYS2050	S01	10328	MW	8:30-9:50(09)	'To Be Arranged'

PHYS 2060. Quantum Mechanics.
No description available.

Spr	PHYS2060	S01	20297	MW	8:30-9:50(02)	'To Be Arranged'

PHYS 2070. Advanced Quantum Mechanics.
No description available.

Fall	PHYS2070	S01	10329	MWF	10:00-10:50(14)	'To Be Arranged'

PHYS 2100. General Relativity.
This graduate course in general relativity and cosmology will cover the principles of Einstein's general theory of relativity, differential geometry, the first order formulation of general relativity (Einstein-Cartan theory), experimental tests of general relativity and black holes. The second half of the course will focus on relativistic cosmology with a focus on its interface with field theory.

PHYS 2140. Statistical Mechanics.
No description available.

Spr	PHYS2140	S01	20298	TTh	1:00-2:20(08)	'To Be Arranged'

PHYS 2170. Introduction to Nuclear and High Energy Physics.
No description available.

PHYS 2280. Astrophysics and Cosmology.
This course serves as a graduate-level introduction to modern cosmology, including current topics of research on both observational and theoretical fronts. Topics include relativistic cosmology, inflation and the early Universe, observational cosmology, galaxy formation. Prerequisites for undergraduates: PHYS 1280 and PHYS 1530.

PHYS 2300. Quantum Theory of Fields I.
No description available.

Spr	PHYS2300	S01	20299	TTh	2:30-3:50(11)	'To Be Arranged'

PHYS 2320. Quantum Theory of Fields II.
No description available. Instructor permission required.

Fall	PHYS2320	S01	10330	TTh	2:30-3:50(12)	'To Be Arranged'

PHYS 2340. Group Theory.
Offered every other year.

PHYS 2410. Solid State Physics I.
No description available.

Fall	PHYS2410	S01	10331	MWF	1:00-1:50(08)	'To Be Arranged'

PHYS 2420. Solid State Physics II.
The goal of the course is to explain the effects of interactions between the electrons on the properties of quantum materials. In particular, upon completing the course you will acquire deep understanding of the physics of conductors, symmetry broken phases and strongly interacting topological phases such as Hall effect. We will particularly concentrate on the phenomenology of these systems.

Spr	PHYS2420	S01	20300	TTh	1:00-2:20(08)	'To Be Arranged'

PHYS 2430. Quantum Many Body Theory.
No description available.

Fall	PHYS2430	S01	10332	TTh	10:30-11:50(13)	'To Be Arranged'

PHYS 2450. Exchange Scholar Program.

Fall	PHYS2450	S01	16726	Arranged		'To Be Arranged'
Fall	PHYS2450	S02	16727	Arranged		'To Be Arranged'
Spr	PHYS2450	S01	25291	Arranged		'To Be Arranged'

PHYS 2470. Advanced Statistical Mechanics.
No description available.

PHYS 2550. Applied Machine Learning and AI.
This graduate-level course explores the integration of machine learning (ML) and artificial intelligence (AI) techniques in various branches of physics. With a focus on practical applications, students will gain hands-on experience in leveraging ML and AI to solve complex problems, enhance data analysis, and optimize experimental design in the context of particle physics, astrophysics, and condensed matter physics.

Fall	PHYS2550	S01	18682	TTh	2:30-3:50(12)	(L. Gouskos)

PHYS 2590. Semiconductor Devices.
An introduction to semiconductor device physics and basic electronic properties of semiconductors, including junctions, heterojunction, and fundamental device building blocks. Current and proposed semiconductor devices: field effect transistors, bipolar transistors, quantum-effect devices, and optoelectronic devices. A brief fabrication lab will introduce junction fabrication in the cleanroom. Advanced topics, such as heterojunction bipolar transistors and silicon-on-insulator FETs, are included in the graduate version.

Spr	PHYS2590	S01	26004	MWF	12:00-12:50(01)	(A. Zaslavsky)

PHYS 2600. Computational Physics.
This course provides students with an introduction to scientific computation at the graduate level, primarily as applied to physical science problems. It will assume a basic knowledge of programming and will focus on how computational methods can be used to study physical systems complementing experimental and theoretical techniques. Prerequisites: PHYS 2030, 2050, 2140; the ability to write a simple computer program in Fortran, Matlab, C or C++.

Spr	PHYS2600	S01	20303	TTh	1:00-2:20(08)	'To Be Arranged'

PHYS 2610A. Selected Topics in Modern Cosmology.
Aims to provide a working knowledge of some main topics in modern cosmology. Combines study of the basics with applications to current research.

PHYS 2610B. Theory of Relativity.
No description available.

PHYS 2610C. Selected Topics in Condensed Matter Physics.

PHYS 2610D. Selected Topics in Condensed Matter Physics.
The objective of this course is to introduce recent development in condensed matter physics. Selected topics include: nanoscale physics, materials, and devices; spintronics and magnetism; high temperature superconductivity; strongly correlated systems; Bose-Einstein condensate; and applications of condensed matter physics. In addition to discussing physics, some experimental techniques used in current research will also be introduced. The course will help students broaden their scope of knowledge in condensed matter physics, learn how to leverage their existing background to select and conduct research, and develop a sense of how to build their professional career based on condensed matter physics.

PHYS 2610E. Selected Topics in Physics of Locomotion.
This special topics graduate course deals with the physical processes involved in the locomotion of organisms, with a particular focus on locomotion at small scales in fluids. Topics include mechanisms of swimming motility for microorganisms, fluid mechanics at low Reynolds number, diffusion and Brownian motion, physical actuation, hydrodynamic interactions, swimming in complex fluids, artificial swimmers, and optimization. Prerequisites: (PHYS0470 or ENGN0510) and (PHYS 0500 or ENGN0810 or ENGN1370), or permission of the instructor.

PHYS 2610F. Selected Topics in Collider Physics.
The course will cover basic aspects of conducting precision measurements and searches for new physics at modern high-energy colliders, with the emphasis given to physics at the Large Hadron Collider. The course will cover major aspects of conducting physics analysis from the underlying theory to experimental methods, such as optimization of the analysis, mutivariate analysis techniques, use of statistical methods to establish a signal or set the limit. There will be reading assignments, in-class student presentations, and hands-on exercises offered as the part of the course. Prerequisite: PHYS 1170 or 2170. Open to graduate students in Physics and Math.

PHYS 2620A. Astrophysical and Cosmological Constraints on Particle Physics.
No description available.

PHYS 2620B. Green's Functions and Ordered Exponentials.
No description available.

PHYS 2620C. Introduction to String Theory.
No description available.

PHYS 2620D. Modern Cosmology.
No description available.

PHYS 2620E. Selected Topics in Quantum Mechanics: Fuzzy Physics.
No description available.

PHYS 2620F. Selected Topics in Molecular Biophysics.
No description available.

PHYS 2620G. The Standard Model and Beyond.
Topics to be covered will include: Yang-Mills theory, origin of masses and couplings of particles, effective field theory, renormalization, confinement, lattice gauge theory, anomalies and instantons, grand unification, magnetic monopoles, technicolor, introduction to supersymmetry, supersymmetry breaking, the Minimal Supersymmetric Standard Model, and dark matter candidates. Prerequisite: PHYS 2300.

PHYS 2620H. Quantum Computation, Information, and Sensing.
This course introduces the theory and practice of quantum computation and quantum information with the focus on quantum algorithms. The topics that will be covered are quantum mechanics from the quantum computing perspective, quantum measurement, quantum sensing, quantum gates, quantum algorithms, quantum error correction codes, quantum entanglement and applications in quantum communication. To demonstrate the ability to perform independent research and literature review, students will write a final report on quantum computing/quantum information topics.

PHYS 2620J. Statistical Physics in Inference and (Deep) Learning.
In this course students will explore the statistical physics principles underlying probabilistic inference and various neural network architectures. The course is designed to bridge the gap between teaching approaches to modern statistical physics that are either purely theoretical, or focus largely on its applications in data analysis. To that end, there will be a conscious effort to study topics such as: MaxEnt principle, variational methods, Hebb’s rule, bias-variance tradeoff, regularization, and others with analytical derivations as well as worked-out code examples in Jupyter notebooks. The course will also provide a space for students to interrogate and reflect on the ethical, political, and policy frameworks that are urgently needed in the age of deep learning.

PHYS 2630. Biological Physics.
The course is the graduate version of Phys 1610, Biological Physics. The topics to be covered include structure of cells and biological molecules; diffusion, dissipation and random motion; flow and friction in fluids; entropy, temperature and energy; chemical reactions and self-assembly; solution electrostatics; action potential and nerve impulses. The graduate level course has additional pre-requsites of Phys 0470 and 1530, or equivalents. It requires homework assignments at the graduate level. The final grades will be assigned separately from those who take the course as Phys 1610, although the two groups may be taught in the same classroom.

Fall	PHYS2630	S01	10324	TTh	2:30-3:50(12)	'To Be Arranged'

PHYS 2640. Introduction to Computational Physics and Data Analysis.
This course introduces upper undergraduate and graduate students to computational methods in physics and data analysis techniques. It covers programming in Python and Mathematica, computational physics fundamentals, and fundamental data analysis methods including statistics, data fitting, and background estimation. The course will use the discovery of the Higgs boson as a case study. Students will engage in practical assignments and a final project to apply learned concepts. Extensive use of Google Colab and Mathematica notebooks will be made to facilitate learning and application. Students are encouraged to bring their laptops to the lectures to perform the examples with the instructor.

Fall	PHYS2640	S01	17292	W	3:00-5:30(10)	(L. Gouskos)

PHYS 2670. Soft Matter.
This course provides an introduction to soft matter: polymers, elastomers, liquid crystals, and colloids. Students in physics, engineering, chemistry, and applied mathematics may find this course useful. Familiarity with classical statistical mechanics (PHYS1530) is required. We will use scaling arguments and simple physical pictures as much as possible.

Spr	PHYS2670	S01	20301	TTh	10:30-11:50(09)	(T. Powers)

PHYS 2710. Seminar in Research Topics.
Instruction via reading assignments and seminars for graduate students on research projects. Credit may vary. Section numbers vary by instructor. Please check Banner for the correct section number and CRN to use when registering for this course.

PHYS 2711. Seminar in Research Topics.
See Seminar In Research Topics (PHYS 2710) for course description. Section numbers vary by instructor. Please check Banner for the correct section number and CRN to use when registering for this course.

PHYS 2790. Quantum Optics.
An introduction to the fundamental theory, mathematical formalism, and applications of quantum optics, the study of light and its interactions with matter at microscopic scales. Topics will include: an introduction to quantum mechanics using the bra-ket (or Dirac) notation, quantization of the electromagnetic fields, generation and detection of single photons, non-classical quantum states (single-mode states, Fock or number states, coherent and squeezed states), phasor diagrams, number-phase uncertainty, quantum theory of photoionization/photodetection, quantum description of mirrors, beam splitters, Mach-Zehnder interferometers, spontaneous emission and parametric downconversion, as well as interaction-free measurements. The course is intended for graduate and senior undergraduate students who would like to understand more advanced concepts in emerging fields, such as quantum computing. The material is self-contained, therefore students who do not have a deep background in quantum mechanics or optics will also be able to take the course proficiently

Spr	PHYS2790	S01	20294	M	3:00-5:30(13)	(D. Pacifici)

PHYS 2970. Preliminary Examination Preparation.
For graduate students who have met the tuition requirement and are paying the registration fee to continue active enrollment while preparing for a preliminary examination.

Fall	PHYS2970	S01	16728	Arranged		(L. Gouskos)
Fall	PHYS2970	S02	16729	Arranged		(J. Roloff)
Spr	PHYS2970	S01	25293	Arranged		(L. Gouskos)

PHYS 2980. Research in Physics.
Section numbers vary by instructor. Please check Banner for the correct section number and CRN to use when registering for this course.

PHYS 2981. Research in Physics.
Section numbers vary by instructor. Please check Banner for the correct section number and CRN to use when registering for this course.

PHYS 2990. Thesis Preparation.
For graduate students who have met the residency requirement and are continuing research on a full time basis.

Fall	PHYS2990	S01	16730	Arranged		'To Be Arranged'
Spr	PHYS2990	S01	25294	Arranged		'To Be Arranged'