Physics and Astronomy

Undergraduate Study

For the undergraduate curriculum in liberal arts and sciences, major in physics, leading to the degree bachelor of science, see Liberal Arts and Sciences, Curriculum.

Physics and astronomy are basic natural sciences which attempt to describe and provide an understanding of both our world and our universe. Physics serves as the underpinning of many different disciplines including the other natural sciences and technological areas. Graduates are proficient in the methods of rigorous scientific analysis, relevant mathematical techniques, and modern computational and laboratory methods. They have a broad knowledge of physics, including mechanics, electricity and magnetism, thermodynamics, and modern physics. They are able to communicate clearly and effectively at general and technical levels. They are prepared to pursue a wide range of careers as a professional physicist, astronomer, or science educator. They are also prepared to pursue advanced studies and careers in areas as diverse as engineering, medicine, law, and business administration. Many opportunities exist for students who terminate their studies with a bachelor's degree, especially when combined with technology studies in other areas. Students who meet the necessary scholastic standards often continue their studies in a graduate college, exploring and contributing to new developments in the field.

The department normally expects each student majoring in physics to complete at least the following courses:

PHYS 241	Principles and Symmetries in Classical Physics I	5
PHYS 242	Principles and Symmetries in Classical Physics II	5
PHYS 321	Introduction to Modern Physics I	3
PHYS 321L	Introductory Laboratory in Modern Physics I	1
PHYS 322	Introduction to Modern Physics II	3
PHYS 322L	Introductory Laboratory in Modern Physics II	1
PHYS 304	Thermal Physics	3
PHYS 306	Physics of Wave Motion	3
PHYS 361	Classical Mechanics	3
PHYS 362	Intermediate Mechanics	3
PHYS 364	Electricity and Magnetism I	3
PHYS 365	Electricity and Magnetism II	3
MATH 317	Theory of Linear Algebra	4
and 3 credits of laboratory work chosen from		3
PHYS 310	Electronic Instrumentation for Experimental Physics	
PHYS 311	Intermediate Laboratory	
PHYS 311T	Intermediate Laboratory for Secondary Physics Teachers	
PHYS 470L	Applied Physics Laboratory	
or		
ASTRO 344L	Astronomy Laboratory	

*PHYS 221 and PHYS 222 may be substituted for PHYS 241 and PHYS 242.

All students are required to earn at least 5 credits in laboratory work in physics in addition to the laboratory components of PHYS 241 and PHYS 242. These 5 credits must be in courses numbered 304 or higher or in approved substitutions. All students must earn at least 26 credits in physics and astronomy courses numbered 304 or higher. The basic list of expected courses is not a rigid requirement and changes in this basic list will be approved by the department curriculum committee on recommendation of the student's adviser when such changes will better serve the student's needs. In particular, students planning a physics major and also seeking certification for high school teaching may, with the approval of their adviser, follow a significantly different program designed to meet their particular needs; these students should consult the department for further information. Further information concerning programs of study, including sample degree programs, is available from the department.

Students majoring in physics who wish an emphasis in astronomy/astrophysics should consider a minor in astronomy (see below). Those planning graduate work in physics or astronomy/astrophysics should add to the basic list the courses PHYS 480 and PHYS 481. Other useful courses include:

MATH 365	Complex Variables with Applications	3
PHYS 426	Mathematical Methods for the Physical Sciences	3
PHYS 496	Modern Optics	3
STAT 447	Statistical Theory for Research Workers	4
One or more of the following may also be added according to interest		
ASTRO 405	Astrophysical Processes	
PHYS 421	Ultrafast Laser Science and Spectroscopy	
PHYS 432	Molecular and Cell Biophysics	
PHYS 461	Physics of Biomolecules	
PHYS 511	Condensed Matter Physics I	
PHYS 526	Particle and Nuclear Physics	
PHYS 541	General Relativity	

The department offers a minor in physics which may be earned by completing 20 credits in physics courses chosen as follows:

PHYS 241	Principles and Symmetries in Classical Physics I	5
PHYS 242	Principles and Symmetries in Classical Physics II	5
PHYS 321	Introduction to Modern Physics I	3
One of the following		
PHYS 321L	Introductory Laboratory in Modern Physics I	
PHYS 322L	Introductory Laboratory in Modern Physics II	
PHYS 310	Electronic Instrumentation for Experimental Physics	
PHYS 311	Intermediate Laboratory	
PHYS 311T	Intermediate Laboratory for Secondary Physics Teachers	
Other acceptable courses		
PHYS 304	Thermal Physics	
PHYS 306	Physics of Wave Motion	
PHYS 322	Introduction to Modern Physics II	
PHYS 361	Classical Mechanics	
PHYS 362	Intermediate Mechanics	
PHYS 364	Electricity and Magnetism I	
PHYS 365	Electricity and Magnetism II	
PHYS 421	Ultrafast Laser Science and Spectroscopy	
PHYS 432	Molecular and Cell Biophysics	
PHYS 461	Physics of Biomolecules	
PHYS 480	Quantum Mechanics I	
PHYS 481	Quantum Mechanics II	
PHYS 496	Modern Optics	
*PHYS 221 and PHYS 222 may be substituted for PHYS 241 and PHYS 242		

The department offers a minor in astronomy which may be earned by completing 15 credits chosen as follows:

ASTRO courses *		12-15
3 credits from the following (if only 12 Astro credits)		3
PHYS 304	Thermal Physics	
PHYS 321	Introduction to Modern Physics I	
PHYS 361	Classical Mechanics	
PHYS 362	Intermediate Mechanics	
PHYS 364	Electricity and Magnetism I	
PHYS 365	Electricity and Magnetism II	
PHYS 480	Quantum Mechanics I	
PHYS 481	Quantum Mechanics II	
PHYS 496	Modern Optics	

* must include ASTRO 344L Astronomy Laboratory and may include one of the courses ASTRO 120 The Sky and the Solar System, ASTRO 150 Stars, Galaxies, and Cosmology or ASTRO 250 Astronomy Bizarre

12 or more credits must be at the 300 level or higher. Note that only ASTRO 344L may be used to satisfy both the requirements of a physics major and an astronomy minor.

Communication Proficiency requirement: The department requires a grade of C or better in each of ENGL 150 and ENGL 250 (or ENGL 250H), and a C– or better in ENGL 302, ENGL 305, ENGL 309 or ENGL 314. Students are also encouraged to study at least one foreign language.

The expected outcomes for students in these programs are:

1. a broad knowledge of physics, including mechanics, electricity and magnetism, thermodynamics, wave motion and modern physics
2. proficiency in laboratory methods
3. proficiency in modern scientific computational methods
4. a sound foundation in the liberal arts including proficiency in communication skills.

In addition to the performance on exams and course grades, information on evaluating of the success in meeting these goals is obtained by:

1. an annual written survey of all students majoring in the program
2. an annual written survey of all graduating seniors
3. a periodic written survey of program alumni
4. student evaluations of all courses
5. adviser evaluations
6. a bimonthly meeting of program majors with the department chair

Graduate Study

The department offers studies for the degrees master of science and doctor of philosophy with majors at both levels in applied physics, astrophysics, condensed matter physics, high energy physics, nuclear physics, and physics; and minor credit courses for students majoring in other departments.

Facilities of various research groups of the department, the Ames Laboratory, and the Applied Science Center, including the Microelectronics Research Center, are available for research.

Students with bachelor's degrees in physics or astronomy from other institutions ordinarily will qualify for graduate study at Iowa State provided they have satisfactorily completed course work similar to that suggested for undergraduate majors here intending to go on to graduate school. In some cases additional instruction at the intermediate level may be required.

Graduates have a broad understanding of physical science, as well as mastery of state-of-the-art methods in their area of specialization. They are able to communicate effectively to a wide range of audiences, from the general public to research colleagues. Their skills in rigorous scientific thinking prepare them for leadership in the broader community. They are skilled in carrying out research, communicating research results, and soliciting research support. They have considerable teaching experience. They have developed problem solving skills that prepare them for careers in either industry or academia.

All candidates for an advanced degree in physics are expected to complete:

PHYS 531	Statistical Mechanics	3
PHYS 564	Advanced Classical Mechanics	3
PHYS 571	Electricity and Magnetism I	3
PHYS 572	Electricity and Magnetism II	3
PHYS 591	Quantum Physics I	4
PHYS 592	Quantum Physics II	4

Candidates for an advanced degree in applied physics are expected to complete:

PHYS 571	Electricity and Magnetism I	3
PHYS 591	Quantum Physics I	4
PHYS 470L	Applied Physics Laboratory	2-5
PHYS 699	Research	arr †
PHYS 572	Electricity and Magnetism II	3
or PHYS 531	Statistical Mechanics	

† Arranged with instructor.

Candidates for an advanced degree in astrophysics should complete:

PHYS 531	Statistical Mechanics	3
PHYS 564	Advanced Classical Mechanics	3
PHYS 571	Electricity and Magnetism I	3
PHYS 591	Quantum Physics I	4
ASTRO 505	Astrophysical Processes	3
ASTRO 510	Observational Astrophysics	3

Astrophysics Ph.D. candidates must take at least three of the 580 level Astro courses, while candidates for the Research Masters must take at least two 580 level Astro courses.

Except for the applied physics major where a thesis is always required, the degree master of science is offered both with and without thesis. For all areas of study except applied physics the basic requirements for the M.S. are the same: at least 30 credits of acceptable graduate work must be completed, not less than 21 of which must be in physics or astronomy. Students must complete not less than 6 credits from outside their major area, with 3 credits being required from outside the department, and 3 credits from a 500 or 600 level course in another area of specialization. Students choosing a M.S. degree with thesis may apply up to 8 credits of 699 but no credits of 599 toward the minimum 30 credits. Students choosing a degree without thesis should apply 2 credits of 599, but may not apply any credits of 699 toward the minimum 30 credits.

Students whose major area is applied physics must complete at least 30 credits of acceptable graduate work for the M.S. degree and not less than 19 credits of these must be in the required courses listed above; the remaining 11 credits of the 30 credit minimum may be chosen freely either from within the student's major area or from without and either from the department or outside, but it should be noted that not more than 3 credits of PHYS 699 Research may be applied toward the 30 credit minimum.

In addition to course work in the major area of study, all candidates for the Ph.D. degree must complete 12 credits from outside this area. Of these 6 must be taken from other departments and 6 must be taken from the department with the additional constraint that this latter 6 must include at least one 500 or 600 level introductory course in another area of specialization. Each candidate for the Ph.D. degree is required to teach one year of elementary physics or astronomy.

Graduate students interested in a physics minor should contact the department for requirements.

Courses primarily for undergraduates:

ASTRO 102. North Star Astronomy.
Cr. 1. F.S.
An entirely web-based course covering topics in observing the sky and navigation by the stars for students with little or no previous experience. The course combines material on common naked-eye phenomena, such as daily and seasonal variations in the sky, with information on how these helped navigators determine where they are on Earth. The course "lectures" are on-line, interactive units with build in exercises, hands-on (offline) activities and layers of help. Graded homework and quizzes are administered via Web-CT. Students who take Astro 120 may count credit in only one of Astro 102 or 103 toward graduation.

ASTRO 103. Evening Star.
Cr. 1. F.S.
An entirely web-based course covering topics in celestial mechanics ("Rocket science!") for students with little or no previous experience. It combines the geography of the solar system with discussion of methods of traveling to the other planets. The course "lectures" are on-line, interactive units with built-in exercises, hands-on (offline) activities, and layers of help. Graded homework and quizzes are administered via WebCT. Students who take Astro 120 may count credit in only one of Astro 102 or 103 toward graduation.

ASTRO 106. Earth and Space Science for Elementary Education Majors.
(Cross-listed with GEOL). (2-0) Cr. 2. F.S. *Prereq: Major in elementary or early childhood education.*
Fundamental concepts of Earth and Space Science, including the solar system, weather and climate, water and soils, plate tectonics, and geologic hazards. Online course format.

ASTRO 106L. Earth and Space Science for Elementary Education Majors: Laboratory.
(Cross-listed with GEOL). (0-2) Cr. 1. F.S. *Prereq: Restricted to elementary and early childhood education majors; to be taken concurrently with GEOL 106/ ASTRO 106*
Inquiry-based lab exploring fundamental concepts of Earth and Space Science, including the solar system, weather and climate, water and soils, plate tectonics, and geologic hazards. Must be taken concurrently with GEOL/ASTRO 106.

ASTRO 120. The Sky and the Solar System.
(3-0) Cr. 3. F.S.SS.
For the nonscientist. The sky: constellations; motions of the sun, moon, and planets; seasons and the calendar; eclipses. The solar system: origin and evolution; characteristics of the sun, planets, satellites, comets, meteorites, and asteroids. Extensive use of the planetarium is included. Students who take Astro 120 may count credit in only one of Astro 102 or 103 toward graduation.

ASTRO 125L. The Sky and the Solar System Laboratory.
(0-2) Cr. 1. F.S. *Prereq: Concurrent or previous enrollment in ASTRO 120*
Laboratory course to accompany Astro 120. Students carry out practical exercises involving naked eye and telescopic observing to explore and reinforce ideas covered in Astro 120. Activities based on a sky-simulation computer program and other weather-independent exercises are also included.

ASTRO 150. Stars, Galaxies, and Cosmology.
(3-0) Cr. 3. F.S.
For the nonscientist. Observational aspects of stellar astronomy: motions, distances, sizes, spectra; types of stars; variability; binary systems. Stellar evolution: the birth, life, and death of stars, including supernovae, neutron stars, and black holes. The Milky Way Galaxy: clouds of matter in space, the structure and evolution of our galaxy. Other galaxies, clusters of galaxies, quasars. Theories of the origin of the universe.

ASTRO 250. Astronomy Bizarre.
(3-0) Cr. 3. S. *Prereq: ASTRO 120 or ASTRO 150*
For the nonscientist. New and exciting topics in modern astronomy. Galaxy and star formation. Black holes and pulsars. Colliding galaxies. Quasars. Cosmology, the Big Bang and the future of the universe. Prospects and searches for extraterrestrial life.

ASTRO 290. Independent Study.
Cr. 1-4. Repeatable. *Prereq: Permission of instructor*

ASTRO 342. Introduction to Solar System Astronomy.
(3-0) Cr. 3. F. *Prereq: PHYS 222*
Analytical and comparative studies of solar system objects-planets, satellites, rings, asteroids, comets, meteoroids, and interplanetary dust-with emphasis on the physical processes affecting them, their interactions, and their evolution. Orbital mechanics, including perturbations, stability, and resonances. Tidal forces and effects. Radiation laws and thermal physics with applications. Brief study of the sun as a star, and of stellar evolution. Origin and evolution of the solar system. Detection of other planetary systems. Nonmajor graduate credit.

ASTRO 344L. Astronomy Laboratory.
(1-6) Cr. 3. F. *Prereq: PHYS 222*
Experiments in optical astronomy. Observational techniques, ranging from stellar photometry to CCD imaging. Available instruments include a variety of small telescopes up to 14-inch in size. Class meets at Fick Observatory south of Boone. Nonmajor graduate credit.

ASTRO 346. Introduction to Astrophysics.
(3-0) Cr. 3. S. *Prereq: PHYS 222*
Basic radiation theory; spectra. Observational determination of stellar properties; spectral classification. Binary systems. Stellar structure and evolution. White dwarfs, neutron stars, black holes. The Galaxy: structure and composition; the interstellar medium. Other galaxies; active galaxies; cosmology. Nonmajor graduate credit.

ASTRO 405. Astrophysical Processes.
(Dual-listed with ASTRO 505). (3-0) Cr. 3. F. *Prereq: ASTRO 346 or permission of instructor*
Survey of astrophysical processes relating to stars, galaxies and the Universe. Radiation transport, radiation processes, scattering, kinetic description of plasma, hydrodynamics, magnetohydrodynamics, MHD waves, shocks, properties of systems in local thermodynamic equilibrium, non-thermal systems, astrophysical effects of general relativity.

ASTRO 450. Undergraduate Research.
Cr. 1-6. Repeatable. F.S.SS. *Prereq: Permission of instructor*
Research under supervision of astronomy faculty.

ASTRO 450L. Undergraduate Research.
Cr. 1-6. Repeatable. F.S.SS. *Prereq: ASTRO 344L and permission of instructor*
Laboratory or observational project under supervision of astronomy faculty.

ASTRO 490. Independent Study.
Cr. 1-4. Repeatable, maximum of 9 credits. *Prereq: 6 credits in astronomy, permission of instructor*
No more than 9 credits of Astro 490 may be counted toward graduation.

ASTRO 490H. Independent Study: Honors.
Cr. 1-4. Repeatable, maximum of 9 credits. *Prereq: 6 credits in astronomy, permission of instructor*
No more than 9 credits of Astro 490 may be counted toward graduation.

Courses primarily for graduate students, open to qualified undergraduates:

ASTRO 505. Astrophysical Processes.
(Dual-listed with ASTRO 405). (3-0) Cr. 3. F. *Prereq: ASTRO 346 or permission of instructor*
Survey of astrophysical processes relating to stars, galaxies and the Universe. Radiation transport, radiation processes, scattering, kinetic description of plasma, hydrodynamics, magnetohydrodynamics, MHD waves, shocks, properties of systems in local thermodynamic equilibrium, non-thermal systems, astrophysical effects of general relativity.

ASTRO 510. Observational Astrophysics.
(2-3) Cr. 3. Alt. F., offered 2011. *Prereq: ASTRO 405 or ASTRO 505*
Techniques in optical and near-IR astronomy, including spectroscopy and CCD photometry. Emphasis on projects involving proficiency in the use of research telescopes and modern instrumentation. Project topics range from photometric studies of pulsating and binary star systems to deep CCD imaging of faint nebulae and galaxies.

ASTRO 580. Stellar Astrophysics.
(3-0) Cr. 3. Alt. S., offered 2013. *Prereq: ASTRO 405 or ASTRO 505*
The interior structure and atmospheric properties of stars: Stellar structure equations and constitutive relations: energy generation, energy transport by radiation and convection; equation of state, nuclear energy generation and nucleosynthesis. Numerical and analytic solutions to the equations of structure and evolution. Observational connections through the theory of radiative transfer. Line and continuum processes and sources of opacity. Non-LTE and statistical equilibrium. Line profiles. Interpretation of stellar spectra: temperature, pressure, and abundance determinations. Stellar evolution from formation to final phases.

ASTRO 582. High Energy Astrophysics.
(3-0) Cr. 3. Alt. F., offered 2012. *Prereq: ASTRO 405 or ASTRO 505*
Interactions of high-energy particles, non-thermal radiation processes, spectral evolution of non-thermal systems, cosmic rays, active galactic nuclei, pulsars, neutrinos, measurement techniques for relativistic charged particles, high energy photons, and neutrinos.

ASTRO 584. Galactic Astronomy.
(3-0) Cr. 3. Alt. S., offered 2012. *Prereq: ASTRO 405 or ASTRO 505*
Overall structure of our Galaxy and the interstellar medium. Physical processes in the interstellar medium (e.g., heating and cooling mechanisms, turbulence). Observational techniques for studying the interstellar medium. Kinematics and chemical evolution of the Galaxy.

ASTRO 586. Extragalactic Astronomy.
(3-0) Cr. 3. Alt. F., offered 2011. *Prereq: ASTRO 405 or ASTRO 505*
Galaxy evolution, dynamics of external galaxies, evolution and classification of galaxies, groups and clusters of galaxies, extragalactic radio sources, quasars, structure formation, cosmological models and their observational consequences.

ASTRO 590. Special topics.
Cr. arr. Repeatable.

ASTRO 599. Creative Component.
Cr. arr. *Prereq: Permission of instructor*
Individually directed study of research-level problems for students electing the nonthesis M.S. option in astronomy.

Courses for graduate students:

ASTRO 650. Advanced Seminar.
(1-0) Cr. 1. Repeatable. F.S.
Topics of current interest in astronomy and astrophysics. Offered on a satisfactory-fail basis only.

ASTRO 660. Advanced Topics in Astronomy and Astrophysics.
Cr. 1-3. Repeatable. F.S.
Topics in stellar, galactic, and extragalactic astronomy, including stellar evolution, solar physics, variable stars, compact objects, the interstellar medium, active galaxies and quasars, formation and evolution of galaxies, cosmology, high energy astrophysics, advanced observational techniques, and astrophysical applications of hydrodynamics.

ASTRO 675. Advanced Stellar Astrophysics.
(3-0) Cr. 3. Alt. S., offered 2012. *Prereq: ASTRO 405 or ASTRO 505; and ASTRO 580*
Advanced topics in stellar astrophysics. Dynamic and extended atmospheres, chromospheres, coronae, and stellar winds. MHD, stellar activity, and dynamo theory. Radiative transfer and the transition from extended atmospheres to the interstellar medium. Diffusive processes in stellar atmospheres and interiors. Techniques for quantitative analysis of planetary and stellar spectra including detailed modeling and spectrum synthesis. Evolution in interacting binaries. Nucleosynthesis II. Variable stars. Supernovae. Neutron stars and black holes.

ASTRO 699. Research.
Cr. arr. Repeatable.

Courses primarily for undergraduates:

PHYS 101. Physics for the Nonscientist.
(3-0) Cr. 3. F.S.
Survey of the principal areas of both classical and modern physics. Emphasis on the nature of the physical universe and the application of physical principles to life in the modern world. Not suitable to meet a general physics requirement for natural science majors.

PHYS 102L. Physical Sciences for Elementary Education.
(Cross-listed with CHEM). (1-5) Cr. 3. S. *Prereq: MATH 195 or MATH 140*
Introduction to physics and chemistry via weekly, guided-inquiry laboratories. Topics to include states of matter and changes in states of matter, sound, light, electricity, magnetism, heat, forces and how they are related to an object's motion.

PHYS 111. General Physics.
(4-2) Cr. 5. F.S.SS. *Prereq: 1 1/2 years of high school algebra, 1 year of geometry, 1 semester of trigonometry*
General background in physical concepts, principles, and methods for those who do not plan advanced study in physics or engineering. Mechanics, fluids, heat and thermodynamics, vibrations, waves, sound.

PHYS 112. General Physics.
(4-2) Cr. 5. F.S.SS. *Prereq: PHYS 111*
General background in physical concepts, principles, and methods for those who do not plan advanced study in physics or engineering. Electricity and magnetism, ray and wave optics, topics in modern physics.

PHYS 115. Physics for the Life Sciences.
(4-0) Cr. 4. F.S. *Prereq: high school: 1 1/2 yr. algebra, 1 yr. geometry, 1 semester trigonometry*
Emphasis on basic physics principles applied to biological problems. Topics include mechanics, fluids, thermodynamics, heat, light, sound, electricity and magnetism. A coordinated laboratory, Physics 115 laboratory is available.

PHYS 115L. Laboratory in Physics for the Life Sciences.
(0-2) Cr. 1. F.S.
Experiments related to the elementary topics of physics for the life sciences. Mechanics, fluids, thermodynamics, heat, light, sound, electricity and magnetism.

PHYS 198. Physics of Music.
(2-2) Cr. 3. F.
Introductory level course on sound for nonphysics majors. Properties of pure tones and harmonics; human perception of sound; room acoustics; scales; production, and analysis of musical by voice, string, woodwind, brass, and percussion instruments. Not suitable to meet a general physics requirement for natural science majors

PHYS 199. Introductory Seminar.
Cr. R. F.
(1-1) Gain experience in key skills that physicists/astronomers use routinely, but are rarely explicitly taught in formal courses. Participate in faculty-led discussions on frontier areas and careers. Offered on a satisfactory-fail basis only.

PHYS 221. Introduction to Classical Physics I.
(4.5-1) Cr. 5. F.S.SS. *Prereq: Credit or enrollment in MATH 166*
For engineering and science majors. 3 hours of lecture each week plus 3 recitations and 1 laboratory every 2 weeks. Elementary mechanics including kinematics and dynamics of particles, work and energy, linear and angular momentum, conservation laws, rotational motion, oscillations, gravitation. Heat, thermodynamics, kinetic theory of gases; waves and sound.

PHYS 221H. Introduction to Classical Physics I: Honors.
(4.5-1) Cr. 5. F.S. *Prereq: Credit or enrollment in MATH 166*
For engineering and science majors. 3 hours of lecture each week plus 3 recitations and 1 laboratory every 2 weeks. Elementary mechanics including kinematics and dynamics of particles, work and energy, linear and angular momentum, conservation laws, rotational motion, oscillations, gravitation. Heat, thermodynamics, kinetic theory of gases; waves and sound.

PHYS 222. Introduction to Classical Physics II.
(4-2) Cr. 5. F.S.SS. *Prereq: PHYS 221, MATH 166*
3 hours of lecture each week plus 1 recitation and 1 laboratory each week. Electric forces and fields. Electrical currents; DC circuits. Magnetic forces and fields: LR, LC, LCR circuits; Maxwell's equations; ray optics and image formation; wave optics; topics in modern physics.

PHYS 222H. Introduction to Classical Physics II: Honors.
(4-2) Cr. 5. F.S. *Prereq: PHYS 221, MATH 166*
3 hours of lecture each week plus 1 recitation and 1 laboratory each week. Electric forces and fields. Electrical currents; DC circuits. Magnetic forces and fields: LR, LC, LCR circuits; Maxwell's equations; ray optics and image formation; wave optics; topics in modern physics.

PHYS 241. Principles and Symmetries in Classical Physics I.
(4.5-1) Cr. 5. F. *Prereq: Credit or enrollment in MATH 166*
Covers all of mechanics; Kinematics and dynamics of particles, work and energy, linear and angular momentum, conservation laws, rotational motion, oscillations, gravitation, and extremum principles. Topics in kinetic theory, thermodynamics, waves and sound.

PHYS 241H. Principles and Symmetries in Classical Physics I, Honors..
(4.5-1) Cr. 5. F. *Prereq: Credit or enrollment in MATH 166; non-physics majors must have permission*
Covers all of mechanics; Kinematics and dynamics of particles, work and energy, linear and angular momentum, conservation laws, rotational motion, oscillations, gravitation, and extremum principles. Topics in kinetic theory, thermodynamics, waves and sound.

PHYS 242. Principles and Symmetries in Classical Physics II.
(4-2) Cr. 5. S. *Prereq: PHYS 221 or PHYS 241, MATH 166*
Electrostatics, potentials and fields, currents, fields of moving charges, the magnetic field, electromagnetic induction, DC and AC circuits, Maxwell's equations and electromagnetic waves, electric and magnetic fields in matter. Topics in optics, special relativity and modern physics.

PHYS 242H. Principles and Symmetries in Classical Physics II, Honors (Spring)..
(4-2) Cr. 5. S. *Prereq: PHYS 221 or 241, MATH 166*
Electrostatics, potentials and fields, currents, fields of moving charges, the magnetic field, electromagnetic induction, DC and AC circuits, Maxwell's equations and electromagnetic waves, electric and magnetic fields in matter. Topics in optics, special relativity and modern physics.

PHYS 290. Independent Study.
Cr. 1-4. Repeatable. *Prereq: Permission of instructor*

PHYS 298. Cooperative Education.
Cr. R. F.S.SS. *Prereq: Permission of the department cooperative education coordinator; sophomore classification*
Required of all cooperative education students. Students must register for this course prior to commencing each work period.

PHYS 302. The Challenge of Contemporary Physics.
(3-0) Cr. 3. S. *Prereq: Sophomore classification*
A largely nonmathematical but intellectually challenging exploration of physics, which assumes no previous work in the field. Selected material from classical and modern physics establishes the conceptual framework for the study of major areas of contemporary physics, culminating in the discussion of topics at the frontier of present knowledge. Topics vary yearly and may include quarks, lasers, superconductivity, fission and fusion, solid state devices, gravitational waves, string theory, facilities, left handed materials, and quantum computing. Not suitable to meet a general physics requirement for natural science majors.

PHYS 304. Thermal Physics.
(3-0) Cr. 3. F. *Prereq: PHYS 222, MATH 266*
Concepts of temperature, entropy, and other characteristic thermodynamic functions, with application to macroscopic properties of matter. The laws of thermodynamics. Introduction to statistical mechanics, including quantum statistics. Application to black body radiation, crystalline vibrations, magnetic ions in solids, electronic heat capacity of metals. Phase transformations and chemical reactions. Nonmajor graduate credit.

PHYS 306. Physics of Wave Motion.
(3-0) Cr. 3. S. *Prereq: PHYS 222, credit or enrollment in MATH 267*
Oscillating systems including damped and forced oscillations; fluids, geometric optics, water waves, the wave equation, Fourier and Laplace transforms, non-uniform media, cylindrical and spherical waves, polarization, interference and diffraction, transmission lines, non-linear waves.

PHYS 310. Electronic Instrumentation for Experimental Physics.
(2-4) Cr. 4. F. *Prereq: PHYS 222; MATH 166*
Common electrical instruments; power supplies; transducers; passive and active devices, analog integrated circuits, including filters and amplifiers; digital integrated circuits; signal transmission and enhancement. Nonmajor graduate credit.

PHYS 311. Intermediate Laboratory.
Cr. 1-2. Repeatable. S. *Prereq: PHYS 322*
Experiments in classical and modern physics performed independently by each student. Nonmajor graduate credit.

PHYS 311T. Intermediate Laboratory for Secondary Physics Teachers.
(0-6) Cr. 3. Repeatable. S. *Prereq: PHYS 112 or PHYS 222*
Experiments in classical and modern physics performed independently by each student. For students preparing for a career in high school teaching.

PHYS 321. Introduction to Modern Physics I.
(3-0) Cr. 3. F. *Prereq: PHYS 222, credit or enrollment in MATH 266*
Quantum nature of matter: photons, de Broglie's postulate: wave-like properties of matter; Bohr's model of hydrogen atom; Schrodinger equations in one dimension: energy quantization; detailed solutions for potential steps, barriers and wells; one-electron atoms, spin and magnetic interactions; ground states, optical and x-ray excitations of multi-electron atoms.

PHYS 321L. Introductory Laboratory in Modern Physics I.
(0-2) Cr. 1. F. *Prereq: Credit or enrollment in PHYS 321*
Experiments related to the foundations of modern physics. The dual wave and particle character of electrons and photons, statistics, interferometry and x-ray spectroscopy.

PHYS 322. Introduction to Modern Physics II.
(3-0) Cr. 3. S. *Prereq: PHYS 321*
Quantum statistics; lasers; physics of molecules. Properties of solids, including electron band structure, superconductivity and magnetism. Nuclear physics, including nuclear sizes and masses, stability, decay modes, reactions, fission and fusion. Elementary particles, including strangeness, charm, and quarks. Fundamental forces of nature.

PHYS 322L. Introductory Laboratory in Modern Physics II.
(0-2) Cr. 1. S. *Prereq: Credit or enrollment in PHYS 322*
Experiments related to the foundations of modern physics. Radioactive decay, elementary particles, Hall effect, quantization, spectroscopy, statistics and instrumentation.

PHYS 361. Classical Mechanics.
(3-0) Cr. 3. F. *Prereq: PHYS 222, MATH 265, MATH 266*
Newtonian mechanics including forced oscillations, central forces and orbital motion, collisions, moving frames of reference, Lagrange's equations. Nonmajor graduate credit.

PHYS 362. Intermediate Mechanics.
(3-0) Cr. 3. S. *Prereq: PHYS 361*
Rigid body motion; small oscillations, normal modes. Special relativity including length contraction, time dilation, simultaneity, Lorentz transformation, 4-vector covariant formalism, relativistic mechanics. Nonmajor graduate credit.

PHYS 364. Electricity and Magnetism I.
(3-0) Cr. 3. F. *Prereq: PHYS 222*
Static electric and magnetic fields, potential theory; electromagnetism, Maxwell's equations. Nonmajor graduate credit.

PHYS 365. Electricity and Magnetism II.
(3-0) Cr. 3. S. *Prereq: PHYS 364*
Relativistic electromagnetic theory; radiation and propagation of electromagnetic waves; interaction with matter. Nonmajor graduate credit.

PHYS 389. Junior Seminar.
Cr. R. S.
Recommended for all junior physics majors. Career opportunities: graduate school programs and application, job placement, alternative careers, basic skills needed for the job market competition. Offered on a satisfactory-fail basis only.

PHYS 398. Cooperative Education.
Cr. R. F.S.SS. *Prereq: Permission of the department cooperative education coordinator; junior classification*
Required of all cooperative education students. Students must register for this course prior to commencing each work period.

PHYS 399. Seminar on Secondary School Physics.
Cr. 1-2. Repeatable, maximum of 2 credits. F. *Prereq: Permission of instructor*
Review of materials and curricula for secondary school physics presented and discussed by members of the class. Required for approval to teach physics in secondary schools.

PHYS 421. Ultrafast Laser Science and Spectroscopy.
(Dual-listed with PHYS 521). (3-0) Cr. 3. F. *Prereq: PHYS 321, PHYS 365, or equivalent with permission of instructor*
Introduction to ultrafast lasers, nonlinear optics, and their applications. Topics selected from: basic optics, atom-photon interactions, electrodynamics of condensed matter, laser physics, ultrafast and nonlinear optics, ultrashort pulse generation, broadband pulse generation, time-resolved spectroscopy and instrumentation. Nonmajor graduate credit.

PHYS 426. Mathematical Methods for the Physical Sciences.
(3-0) Cr. 3. F. *Prereq: Math 266 or 267*
A fast-paced course primarily for first-year graduate students in physics and chemistry. Emphasis on techniques needed for quantum mechanics and electrodynamics. Functions of a complex variable and contour integration, integral transforms and applications, series methods for ordinary differential equations, Green's functions, Sturm-Liouville problems and orthogonal functions, boundary-value problems for partial differential equations. Nonmajor graduate credit.

PHYS 432. Molecular and Cell Biophysics.
(Dual-listed with PHYS 532). (3-0) Cr. 3. S. *Prereq: PHYS 304 or CHEM 325.*
Quantitative description of biological systems using basic physical laws, including a brief discussion of a variety of biophysical techniques. Topics include: thermodynamics, chemical equilibrium, gene expression, structure and physical properties of nucleic acids and proteins, folding of nucleic acids and proteins, chemical kinetics, catalysis, allosteric enzymes, cell membrane structure and physical properties, and machines in cell membranes. Nonmajor graduate credit.

PHYS 450. Undergraduate Research.
Cr. 1-6. Repeatable. F.S.SS. *Prereq: Permission of instructor*
Theoretical research under supervision of physics faculty.

PHYS 450L. Undergraduate Research.
Cr. 1-6. Repeatable. F.S.SS. *Prereq: PHYS 311, permission of instructor*
Laboratory project under supervision of physics faculty.

PHYS 461. Physics of Biomolecules.
(Dual-listed with PHYS 561). (3-0) Cr. 3. F. *Prereq: PHYS 304 or CHEM 325, BBMB 301, or permission of instructor*
Cell and Molecular Biophysics. Physical techniques used to characterize the structure, dynamics and properties of biomolecules with emphasis on single molecule techniques.

PHYS 470L. Applied Physics Laboratory.
Cr. 2-5. Repeatable. F.S.SS. *Prereq: PHYS 322 and permission of instructor*
Studies in modern experimental techniques via experimentation and simulation in various areas of applied physics, e.g. superconductivity, optical spectroscopy, nuclear magnetic resonance, electron spin resonance, x-ray diffraction, and computation of electronic and structural properties of matter.

PHYS 480. Quantum Mechanics I.
(3-0) Cr. 3. F. *Prereq: PHYS 322, MATH 385*
First semester of a full-year course. A systematic development of the formalism and applications of quantum mechanics. Solutions to the time independent Schrodinger equation for various one-dimensional potentials including the harmonic oscillator; operator methods; Heisenberg picture; angular momentum; the hydrogen atom; spin; symmetry properties. Nonmajor graduate credit.

PHYS 481. Quantum Mechanics II.
(3-0) Cr. 3. S. *Prereq: PHYS 480*
Continuation of 480. Addition of angular momentum; charged particles in electromagnetic fields; time-independent perturbation theory; variational principles; WKB approximation; interaction picture; time-dependent perturbation theory; adiabatic approximation; scattering; selected topics in radiation theory; quantum paradoxes. Nonmajor graduate credit.

PHYS 490. Independent Study.
Cr. 1-4. Repeatable, maximum of 9 credits. *Prereq: 6 credits in physics, permission of instructor*
No more than 9 credits of Phys 490 may be counted toward graduation.

PHYS 490H. Independent Study, Honors.
Cr. 1-4. Repeatable, maximum of 9 credits. *Prereq: 6 credits in physics, permission of instructor*
No more than 9 credits of Phys 490 may be counted toward graduation.

PHYS 496. Modern Optics.
(Cross-listed with E E). (3-0) Cr. 3. S. *Prereq: Credit or enrollment in PHYS 322, PHYS 365, and PHYS 480*
Review of wave and electromagnetic theory; topics selected from: reflection/ refraction, interference, geometrical optics, Fourier analysis, dispersion, coherence, Fraunhofer and Fresnel diffraction, holography, quantum optics, nonlinear optics. Nonmajor graduate credit.

PHYS 498. Cooperative Education.
Cr. R. F.S.SS. *Prereq: Permission of the department cooperative education coordinator; senior classification*
Required of all cooperative education students. Students must register for this course prior to commencing each work period.

Courses primarily for graduate students, open to qualified undergraduates:

PHYS 501. Oral Communication of Physics Seminar.
(2-0) Cr. 1. Repeatable. F.
A practical introduction to communication methods in physics and astronomy classrooms and professional settings. For graduate physics majors only. Offered on a satisfactory-fail basis only.

PHYS 502. Introductory Research Seminar.
Cr. R. F.
(1-1) Discussion by research staff of their research areas, expected thesis research work, and opportunities in the field. For graduate physics majors only. Offered on a satisfactory-fail basis only.

PHYS 511. Condensed Matter Physics I.
(3-0) Cr. 3. S. *Prereq: PHYS 304, credit or enrollment in PHYS 481*
First semester of a full-year course. Free electron model; crystal symmetry; band theory of solids; transport properties; Fermi surface; phonons; semiconductors; crystal surfaces; magnetism; superconductivity.

PHYS 512. Condensed Matter Physics II.
(3-0) Cr. 3. F. *Prereq: PHYS 511*
Continuation of 511. Free electron model; crystal symmetry; band theory of solids; transport properties; Fermi surface; phonons; semiconductors; crystal surfaces; magnetism; superconductivity.

PHYS 521. Ultrafast Laser Science and Spectroscopy.
(Dual-listed with PHYS 421). Cr. 3. F. *Prereq: PHYS 321, PHYS 365, or equivalent with permission of instructor*
Introduction to ultrafast lasers, nonlinear optics, and their applications. Topics selected from: basic optics, atom-photon interactions, electrodynamics of condensed matter, laser physics, ultrafast and nonlinear optics, ultrashort pulse generation, broadband pulse generation, time-resolved spectroscopy and instrumentation.

PHYS 526. Particle and Nuclear Physics.
(4-0) Cr. 4. S. *Prereq: Credit or enrollment in PHYS 481*
Basic properties and structures of nuclei, hadrons, and elementary particles; weak and strong interactions; the Standard Model; accelerators and detectors; nuclear models; nuclear decay and stability; nuclear astrophysics; the Higgs mechanism; the CKM matrix; running coupling constants; relativistic heavy-ion collisions; selected topics beyond the standard model such as SUSY and grand unification.

PHYS 531. Statistical Mechanics.
(3-0) Cr. 3. S. *Prereq: PHYS 304 and credit or enrollment in PHYS 481, MATH 465, credit or enrollment in MATH 365 or MATH 426*
Thermodynamic properties of systems of many particles obeying Boltzmann, Fermi-Dirac, and Bose-Einstein statistics; microcanonical, canonical, and grand canonical ensembles and their application to physical problems; density matrices; introduction to phase transitions; renormalization group theory; kinetic theory and fluctuations.

PHYS 532. Molecular and Cell Biophysics.
(Dual-listed with PHYS 432). (3-0) Cr. 3. S. *Prereq: PHYS 304 or CHEM 325.*
Quantitative description of biological systems using basic physical laws, including a brief discussion of a variety of biophysical techniques. Topics include: thermodynamics, chemical equilibrium, gene expression, structure and physical properties of nucleic acids and proteins, folding of nucleic acids and proteins, chemical kinetics, catalysis, allosteric enzymes, cell membrane structure and physical properties, and machines in cell membranes.

PHYS 534. Symmetry and Group Theory in Physics.
(3-0) Cr. 3. S. *Prereq: Credit or enrollment in PHYS 481*
Theory of groups and group representations; introduction to both point and continuous groups, and their applications in physics.

PHYS 535. Physics of Semiconductors.
(Cross-listed with E E). (3-3) Cr. 4. *Prereq: E E 311 and E E 332*
Basic elements of quantum theory, Fermi statistics, motion of electrons in periodic structures, crystal structure, energy bands, equilibrium carrier concentration and doping, excess carriers and recombination, carrier transport at low and high fields, space charge limited current, photo-conductivity in solids, phonons, optical properties, amorphous semiconductors, heterostructures, and surface effects. Laboratory experiments on optical properties, carrier lifetimes, mobility, defect density, doping density, photo-conductivity, diffusion length of carriers.

PHYS 536. Physics of Semiconductor Devices.
(Cross-listed with E E). (3-0) Cr. 3. *Prereq: E E 535*
P-n junctions, band-bending theory, tunneling phenomena, Schottky barriers, heterojunctions, bipolar transistors, field-effect transistors, negative-resistance devices and optoelectronic devices.

PHYS 541. General Relativity.
(3-0) Cr. 3. F. *Prereq: PHYS 362, MATH 307 or MATH 317*
Tensor analysis and differential geometry developed and used to formulate Einstein field equations. Schwarzschild and Kerr solutions. Other advanced topics may include gravitational radiation, particle production by gravitational fields, alternate gravitational theories, attempts at unified field theories, cosmology.

PHYS 551. Computational Physics.
(0-4) Cr. 2. S. *Prereq: PHYS 365, credit or enrollment in PHYS 481*
Use of modern computational techniques to analyze topics in classical and modern physics. Offered on a satisfactory-fail basis only.

PHYS 561. Physics of Biomolecules.
(Dual-listed with PHYS 461). (3-0) Cr. 3. F. *Prereq: PHYS 304 or CHEM 325, BBMB 301, or permission of instructor; graduate student classification in Science/ Engineering*
Cell and Molecular Biophysics. Physical techniques used to characterize the structure, dynamics and properties of biomolecules with emphasis on single molecule techniques.

PHYS 564. Advanced Classical Mechanics.
(3-0) Cr. 3. S. *Prereq: PHYS 362, MATH 426, MATH 465*
Variational principles, Lagrange's equations, Hamilton's canonical equations, canonical transformations, Hamilton-Jacobi theory, infinitesimal transformations, classical field theory, canonical perturbation theory, classical chaos.

PHYS 571. Electricity and Magnetism I.
(3-0) Cr. 3. F. *Prereq: PHYS 365, MATH 426*
Electrostatics, magnetostatics, boundary value problems, Maxwell's equations, wave phenomena in macroscopic media, wave guides.

PHYS 572. Electricity and Magnetism II.
(3-0) Cr. 3. S. *Prereq: PHYS 571*
Special theory of relativity, least action and motion of charged particles in electromagnetic fields, radiation, collisions between charged particles, multipole fields, radiation damping.

PHYS 590. Special Topics.
Cr. arr. Repeatable. *Prereq: Permission of instructor*
Topics of current interest.

PHYS 590A. Nuclear Physics.
Cr. arr. Repeatable. *Prereq: Permission of instructor*
Topics of current interest.

PHYS 590B. Condensed Matter Physics.
Cr. arr. Repeatable. *Prereq: Permission of instructor*
Topics of current interest.

PHYS 590C. High Energy Physics.
Cr. arr. Repeatable. *Prereq: Permission of instructor*
Topics of current interest.

PHYS 590D. Physics.
Cr. arr. Repeatable. *Prereq: Permission of instructor*
Topics of current interest.

PHYS 590E. Applied Physics.
Cr. arr. Repeatable. *Prereq: Permission of instructor*
Topics of current interest.

PHYS 590F. Biophysics.
Cr. arr. Repeatable. *Prereq: Permission of instructor*
Topics of current interest.

PHYS 591. Quantum Physics I.
(4-0) Cr. 4. F. *Prereq: PHYS 481*
First semester of a full-year course. Postulates of quantum mechanics; time-dependent and time-independent Schrodinger equations for one-,two-, and three-dimensional systems; theory of angular momentum; Rayleigh-Schrodinger time-independent perturbation theory.

PHYS 592. Quantum Physics II.
(4-0) Cr. 4. S. *Prereq: PHYS 591*
Continuation of 591. Variational theorem and WKB method; time-dependent perturbation theory and 2nd quantization of the EM field in Coulomb gauge; method of partial waves and Born approximation for scattering by central potentials; identical particles and symmetry; Dirac and Klein-Gordon equation for free particles; path integral formalism.

PHYS 599. Creative Component.
Cr. arr. *Prereq: Permission of instructor*
Individually directed study of research-level problems for students electing the nonthesis M.S. degree option.

Courses for graduate students:

PHYS 611. Quantum Theory of Condensed Matter.
(3-0) Cr. 3. S. *Prereq: PHYS 512 and PHYS 681 or permission of instructor.*
Quasiparticles in condensed matter: phonons, magnons, photons, electrons. Quantum theory of interacting many body systems: Green's functions and diagrammatic techniques.

PHYS 624. Advanced Nuclear Physics.
(3-0) Cr. 3. *Prereq: PHYS 526 and PHYS 592*
Microscopic few-body and many-body theory; theory of effective Hamiltonians; relativistic nuclear physics; nuclear effects in hadron-nucleus, lepton-nucleus, and nucleus-nucleus reactions.

PHYS 625. Physics of Strong Interactions.
(3-0) Cr. 3. *Prereq: PHYS 681*
Quark model; Quantum Chromodynamics IQCD); perturbation methods for QCD; effective field theories for pions and nucleons; finite temperature field theories; quark-gluon plasma; phase transitions in QCD.

PHYS 637. Elementary Particle Physics I.
(3-0) Cr. 3. *Prereq: PHYS 526 and PHYS 592*
First semester of a full year course. Properties of leptons, bosons, and quarks and their interactions; quantum chromodynamics, Glashow-Weinberg-Salam model, grand unification theories, supersymmetry; modern theoretical techniques and tests of the Standard Model.

PHYS 638. Elementary Particle Physics II.
(3-0) Cr. 3. *Prereq: PHYS 637*
Continuation of 637. Properties of leptons, bosons, and quarks and their interactions; quantum chromodynamics, Glashow-Weinberg-Salam model, grand unification theories, supersymmetry, and superstring theory; modern theoretical techniques.

PHYS 646. Mathematical Modeling of Complex Physical Systems.
(Cross-listed with MATH). (3-0) Cr. 3. S.
Modeling of the dynamics of complex systems on multiple scales: Classical and dissipative molecular dynamics, stochastic modeling and Monte-Carlo simulation; coarse grained nonlinear dynamics, interface propagation and spatial pattern formation.

PHYS 650. Advanced Seminar.
(1-0) Cr. 1. Repeatable. F.S.
Topics of current interest. Offered on a satisfactory-fail basis only.

PHYS 650A. Nuclear Physics.
(1-0) Cr. 1. Repeatable. F.S.
Topics of current interest. Offered on a satisfactory-fail basis only.

PHYS 650B. Condensed Matter Physics.
(1-0) Cr. 1. Repeatable. F.S.
Topics of current interest. Offered on a satisfactory-fail basis only.

PHYS 650C. High Energy Physics.
(1-0) Cr. 1. Repeatable. F.S.
Topics of current interest. Offered on a satisfactory-fail basis only.

PHYS 650D. Physics.
(1-0) Cr. 1. Repeatable. F.S.
Topics of current interest. Offered on a satisfactory-fail basis only.

PHYS 650E. Applied Physics.
(1-0) Cr. 1. Repeatable. F.S.
Topics of current interest. Offered on a satisfactory-fail basis only.

PHYS 650F. Biophysics.
(1-0) Cr. 1. Repeatable. F.S.
Topics of current interest. Offered on a satisfactory-fail basis only.

PHYS 660. Advanced Topics in Physics.
Cr. 1-3. Repeatable. F.S.
Courses on advanced topics and recent developments.

PHYS 660A. Nuclear Physics.
Cr. 1-3. Repeatable. F.S.
Courses on advanced topics and recent developments.

PHYS 660B. Condensed Matter Physics.
Cr. 1-3. Repeatable. F.S.
Courses on advanced topics and recent developments.

PHYS 660C. High Energy Physics.
Cr. 1-3. Repeatable. F.S.
Courses on advanced topics and recent developments.

PHYS 660D. Physics.
Cr. 1-3. Repeatable. F.S.
Courses on advanced topics and recent developments.

PHYS 660E. Applied Physics.
Cr. 1-3. Repeatable. F.S.
Courses on advanced topics and recent developments.

PHYS 660F. Biophysics.
Cr. 1-3. Repeatable. F.S.
Courses on advanced topics and recent developments.

PHYS 681. Quantum Field Theory I.
(3-0) Cr. 3. F. *Prereq: PHYS 564, PHYS 572, PHYS 592*
Quantization of fields (canonical and path integral); Feynman rules; introduction to gauge theories; Quantum Electrodynamics; radiative corrections; renormalization and renormalization group.

PHYS 682. Quantum Field Theory II.
(3-0) Cr. 3. Alt. S., offered 2012. *Prereq: PHYS 681*
Continuation of 681. Systematics of renormalization; renormalization group methods; symmetries; spontaneous symmetry breaking; non-abelian gauge theories; the Standard Model and beyond; special topics.

PHYS 699. Research.
Cr. arr. Repeatable.