PHYSICS (PHYS)

PHYS 113A. Principles of Physics Laboratory - Mechanics. 1 Unit.
The laboratory portion of first semester introductory physics.

PHYS 113B. Principles of Physics Laboratory - Electricity and Magnetism. 1 Unit.
The laboratory portion of the second semester of physics.

PHYS 115. Introductory Physics I. 4 Units.
First part of a two-semester sequence directed primarily towards students working towards a B.A. in science, with an emphasis on the life sciences. Kinematics; Newton's laws; gravitation; simple harmonic motion; mechanical waves; fluids; ideal gas law; heat and the first and second laws of thermodynamics. This course has a laboratory component. Students may earn credit for only one of the following courses: PHYS 115, PHYS 121, PHYS 123.

PHYS 116. Introductory Physics II. 4 Units.
Electrostatics, Coulomb's law, Gauss's law; capacitance and resistance; DC circuits; magnetic fields; electromagnetic induction; RC and RL circuits; light; geometrical optics; interference and diffraction; special relativity; introduction to quantum mechanics; elements of atomic, nuclear and particle physics. This course has a laboratory component. Students may earn credit for only one of the following courses: PHYS 116, PHYS 122, PHYS 124. Prereq: PHYS 115.

PHYS 121. General Physics I - Mechanics. 4 Units.
Particle dynamics, Newton's laws of motion, energy and momentum conservation, rotational motion, and angular momentum conservation. This course has a laboratory component. Recommended preparation: MATH 121 or MATH 123 or MATH 125 or one year of high school calculus. Students who do not have the appropriate background should not enroll in PHYS 121 without first consulting the instructor. Students may earn credit for only one of the following courses: PHYS 115, PHYS 121, PHYS 123.

PHYS 122. General Physics II - Electricity and Magnetism. 4 Units.
Electricity and magnetism, emphasizing the basic electromagnetic laws of Gauss, Ampere, and Faraday. Maxwell's equations and electromagnetic waves, interference, and diffraction. This course has a laboratory component. Students may earn credit for only one of the following courses: PHYS 116, PHYS 122, PHYS 124. Prereq: PHYS 121 or PHYS 123. Prereq or Coreq: MATH 122 or MATH 124 or MATH 126.

PHYS 123. Physics and Frontiers I - Mechanics. 4 Units.
The Newtonian dynamics of a particle and of rigid bodies. Energy, momentum, and angular momentum conservation with applications. A selection of special frontier topics as time permits, including fractals and chaos, special relativity, fluid mechanics, cosmology, quantum mechanics. This course has a laboratory component. Admission to this course is by invitation only. Students may earn credit for only one of the following courses: PHYS 115, PHYS 121, PHYS 123.

PHYS 124. Physics and Frontiers II - Electricity and Magnetism. 4 Units.
Time-independent and time-dependent electric and magnetic fields. The laws of Coulomb, Gauss, Ampere, and Faraday. Microscopic approach to dielectric and magnetic materials. Introduction to the usage of vector calculus; Maxwell's equations in integral and differential form. The role of special relativity in electromagnetism. Electromagnetic radiation. This course has a laboratory component. Students may earn credit for only one of the following courses: PHYS 116, PHYS 122, PHYS 124. Prereq: PHYS 123 and (MATH 122 or MATH 124).

PHYS 150. An Introduction to the Universe and to the Meaning of Everything. 3 Units.
This class will tackle the big questions of human existence including the origins of the universe, life and human civilization, the nature of thought and the development of our tools for examining these questions such as science, mathematics, computing, engineering, philosophy and art. The course will be anchored in lectures by the two primary instructors but will feature a large cast of guest lecturers representing many departments of the College of Arts and Sciences and other schools and colleges at the University as well as neighboring institutions such as the Museum of Art and the Museum of Natural History. A major goal of the course is to introduce students to the extraordinary intellectual resources of the University and its affiliated institutions. Offered as ARTH 150 and PHYS 150.

PHYS 166. Physics Today and Tomorrow. 1 Unit.
This course will provide students with an opportunity to learn about the most exciting and timely research areas in physics, as well as other topics germane to being a professional physicist. These discussions will cover fields such as nanoscience, ultrafast optics, exotic materials, biophysics, cosmology, string theory and the role of physicists in developing new technologies. Each week a member of the faculty will meet with students to discuss a topic of current interest, how a physicist approaches the problem, and how physicists interact with others to find a solution. Other topics germane to being a professional physicist also will be discussed, including the relationship among academic, industrial, and governmental laboratories; ethics, and non-traditional careers for students trained in physics.

PHYS 203. Analog and Digital Electronics. 4 Units.
Elements of both analog and digital electronics from the practical viewpoint of the experimental scientist; AC circuits, linear and non-linear operation of op-amps, logic gates, flip-flops, counters, display, memory, transducers, A/D and D/A conversion. Laboratory work involves quantitative investigation of the operation of all these elements, together with projects that explore their combination. Recommended preparation: PHYS 122 or PHYS 124.

PHYS 204. Advanced Instrumentation Laboratory. 4 Units.
Principles of experimental design; limits of resolution via band-width, thermal noise, background signals; data acquisition and control by computer; computer simulation; signal processing techniques in frequency and time domains, FFT, correlations, and other transform methods; counting techniques. Applications include lock-in amplifiers, digitizing oscilloscopes and data acquisition systems. Prereq: PHYS 203.

PHYS 208. Instrumentation and Signal Analysis Laboratory. 4 Units.
AC circuit theory, Fourier series, discrete Fourier series. Fourier integral, discrete Fourier integral; analysis in time and frequency domains, correlation, cross-correlation and other transform techniques; computer control of experiments via IEEE488 interface; advanced instrumentation; DMM, arbitrary waveform generator, multiplexing and digitizing oscilloscopes; experimental design, noise; design, construction, and testing of a lock-in amplifier. Prereq: ENGR 210.

PHYS 221. Introduction to Modern Physics. 3 Units.
Concepts in special relativity, statistical mechanics and quantum mechanics. Applications to atomic structure, and selected topics in nuclear, condensed matter physics, particle physics, and cosmology. Prereq: PHYS 116 or PHYS 122 or PHYS 124.

PHYS 250. Computational Methods in Physics. 3 Units.
Numerical methods, data analysis, and error analysis applied to physical problems. Use of personal computers in the solution of practical problems encountered in physics. Interpolation, roots of equations, integration, differential equations, Monte Carlo techniques, propagation of errors, maximum likelihood, convolution, Fourier transforms. Prereq: ENGR 131 or CSDS 132 or ECSE 132. Prereq or Coreq: MATH 224 and PHYS 221.

PHYS 260. Introduction to Climate Change: Physics, Forecasts, and Strategies. 3 Units.
This is a one-semester introduction to the physical processes that determine Earth's past, present, and future climate. The course focuses on quantitatively understanding the human impact on climate, including the historical development of steadily more sophisticated physical models, and ever more complete data. Particular emphasis will be placed on understanding climate change projections, as well as the ethical, political, economic, and communications challenges associated with various strategies going forward. The course is appropriate for all majors. Offered as EEPS 260 and PHYS 260.

PHYS 261. Our Knowledge of Climate Change: What do we know and how do we know it?. 3 Units.
Traditional theories of knowledge have concentrated on the actions and beliefs of individuals, and how they marshal evidence from the world to support or refute their scientific hypotheses. This traditional epistemological framework has been challenged by the developments of the modern era of Big Science, resulting in the development of new approaches to a social epistemology of science. Reflective of how science is done, this epistemological framework in turn can provide guidance for the robust prosecution of the scientific enterprise. Perhaps nowhere is this more important than in climate science, where on the one hand the underlying dynamics of climate change pose an existential threat to our civilization, and on the other, there are active and well organized efforts to derail the scientific process and to denigrate the scientists. This course will first develop classical notions of the epistemology of science, including the role of models and issues of uncertainty (statistical, systematic, and gross) as well as the challenges of developing a robust scientific process resistant to fraud. These issues will be illustrated by consideration of various classical experiments. The course will then expand the epistemological framework to the collaborative context of modern big science, illustrating the issues by examples from the field of high energy physics (which saw the development of the World Wide Web by CERN, the European Organization for Nuclear Research, to allow physicists from around the world to share and collectively analyze data). With this in hand the course will explore the history and current state of climate science in the framework of a social epistemology of big science. Students will develop a good understanding of the role of hierarchical models of climate science, the empirical basis for our current understanding of anthropogenic climate change, the role and development of international coordination of climate science and its implications for policy, and the challenges posed by hostile, well-organized efforts to disrupt the scientific process, the public understanding of the science, and ultimately the processes necessary for addressing the challenges of climate change. Offered as PHIL 261 and PHYS 261.

PHYS 301. Advanced Laboratory Physics I. 3 Units.
Problem solving approach with a range of available experiments in classical and modern physics. Emphasis on experimental techniques, data and error analysis, and the formal presentation of the work performed. Recommended preparation: PHYS 204. Counts as a Disciplinary Communication course. Prereq: Physics or Astronomy Major or Minor. Coreq: PHYS 303.

PHYS 302. Advanced Laboratory Physics II. 4 Units.
Several projects using research-quality equipment in contemporary fields of experimental physics. Each requires reading appropriate literature, choosing appropriate instrumentation, performing data acquisition and analysis, and writing a technical paper. Topics include particle counting techniques, neutron activation, gamma-ray spectroscopy, a range of condensed matter experiments including temperature dependent properties between 10 and 350 K, modern optics, ultrahigh vacuum surface science. Prereq: PHYS 301.

PHYS 303. Advanced Laboratory Physics Seminar. 1 Unit.
Students will discuss various issues associated with physics research. These include how to judge the quality of an experiment and data (error analysis), how to present your work in written and oral formats, safety and ethical concerns in the laboratory. Recommended preparation: PHYS 250. Counts as a Disciplinary Communication course. Counts as a SAGES Departmental Seminar course.

PHYS 310. Classical Mechanics. 3 Units.
Lagrangian formulation of mechanics and its application to central force motion, scattering theory, rigid body motion, and systems of many degrees of freedom. Recommended preparation: PHYS 221 and either MATH 223 or MATH 227.

PHYS 313. Thermodynamics and Statistical Mechanics. 3 Units.
Thermodynamic laws, entropy, and phase transitions from the quantum mechanical viewpoint. Gibbs and Boltzmann factors. Ideal, degenerate fermion, degenerate boson, photon, and phonon gases. Correlation functions and transport phenomena. Applications ranging from solid state physics to astrophysics. Prereq: PHYS 221.

PHYS 315. Introduction to Solid State Physics. 3 Units.
Characterization and properties of solids; crystal structure, thermal properties of lattices, quantum statistics, electronic structure of metals and semiconductors. PHYS 415 for graduate students in engineering and science. (May not be taken for departmental credit by graduate students in the Department of Physics.) Prerequisite may be waived with consent of department. Recommended preparation for PHYS 415: PHYS 331. Offered as PHYS 315 and PHYS 415. Prereq: PHYS 331 or PHYS 481.

PHYS 316. Introduction to Nuclear and Particle Physics. 3 Units.
The physics of nuclei and elementary particles; experimental methods used to determine their properties; models and theories developed to describe their structure. Prereq: PHYS 331 or PHYS 481.

PHYS 317. Engineering Physics Laboratory I. 3 Units.
Laboratory course for engineering physics majors. Emphasis is on experimental techniques, data and error analysis, and written and oral presentation of work. Four experiments drawn from classical and modern physics are carried out. These emphasize condensed matter, material and optical physics. Experiments include electric fields, resistivity of materials, optical interference, chaotic systems, and spectroscopy. Design of data analysis systems and software is required. Counts as a Disciplinary Communication course. Prereq: PHYS 208. Coreq: PHYS 303.

PHYS 318. Engineering Physics Laboratory II. 4 Units.
Laboratory course for engineering physics majors. Several projects using research-quality equipment in contemporary fields of experimental physics. Open-ended experiments each require reading appropriate literature, designing the experiment, performing data analysis, and writing a technical paper. Topics are drawn from areas of modern physics, and concentrate on condensed matter, material, and optical physics. Prereq: PHYS 317.

PHYS 320. Introduction to Biological Physics. 3 Units.
This course explores the intersection of physics and biology: how do fundamental physical laws constrain life processes inside the cell, shaping biological organization and dynamics? We will start at the molecular level, introducing the basic ideas of nonequilibrium statistical physics and thermodynamics required to describe the fluctuating environment of the cell. This allow us to build up a theoretical framework for a variety of elaborate cellular machines: the molecular motors driving cell movement, the chaperones that assist protein folding, the information-processing circuitry of genetic regulatory networks. The emphasis throughout will be on simple, quantitative models that can tackle the inherent randomness and variability of cellular phenomena. We will also examine how to verify these models through the rich toolbox of biophysical experimental and computational technologies. The course should be accessible to students from diverse backgrounds in the physical and life sciences: we will explain both the biological details and develop the necessary mathematical / physical ideas in a self-contained manner. Offered as PHYS 320 and PHYS 420. Prereq: (MATH 122 or MATH 124) and (ENGR 131 or CSDS 132 or ECSE 132).

PHYS 321. Advanced Computational Methods in Physics. 3 Units.
Advanced numerical methods applied to physical problems. Use of personal computers in the solution of practical problems encountered in physics. Topics may include ordinary and partial differential equations, linear algebra, and Monte Carlo techniques. Focus is placed on developing, documenting, testing, and presenting solutions to physical problems. Standard, collaborative tools commonly used in research groups will be employed. Offered as PHYS 321 and PHYS 421. Prereq: PHYS 250.

PHYS 324. Electricity and Magnetism I. 3 Units.
First half of a sequence that constitutes a detailed study of the basics of electromagnetic theory and many of its applications. Electrostatics and magnetostatics of free space, conductors, dielectric and magnetic materials; basic theory illustrated with applications drawn from condensed matter physics, optics, plasma physics, and physical electronics. Prereq: PHYS 116 or PHYS 122 or PHYS 124.

PHYS 325. Electricity and Magnetism II. 3 Units.
(Continuation of PHYS 324.) Electrodynamics, Maxwell's equations, electromagnetic waves, electromagnetic radiation and its interaction with matter, potential formulation of electromagnetism, and relativity. Prereq: PHYS 324.

PHYS 326. Physical Optics. 3 Units.
Geometrical optics and ray tracing, wave propagation, interaction of electromagnetic radiation with matter, interference, diffraction, and coherence. Supplementary current topics from modern optics such as nonlinear optics, holography, optical trapping and optical computing. Prerequisite(s) may be waived with consent of department. Offered as PHYS 326 and PHYS 426. Prereq: PHYS 122 or PHYS 124.

PHYS 327. Laser Physics. 3 Units.
An introduction to theoretical and practical quantum electronics covering topics in quantum optics, laser physics, and nonlinear optics. Topics to be addressed include the physics of two-level quantum systems including the density matrix formalism, rate equations, and semiclassical radiation theory; laser operation including oscillation, gain, resonator optics, transverse and longitudinal modes, Q-switching, mode-locking, and coherence; and nonlinear optics including the nonlinear susceptibility, parametric interactions, stimulated processes, and self-action. Recommended preparation for PHYS 427: PHYS 331 or PHYS 481. Offered as PHYS 327 and PHYS 427. Prereq: PHYS 331 or PHYS 481.

PHYS 328. Cosmology and the Structure of the Universe. 3 Units.
Distances to galaxies. The content of the distant universe. Large scale structure and galaxy clusters. Physical cosmology. Structure and galaxy formation and evolution. Testing cosmological models. Offered as ASTR 328, PHYS 328, ASTR 428, and PHYS 428. Prereq: ASTR 222.

PHYS 329. Independent Study. 1 - 4 Units.
An individual reading course in any topic of mutual interest to the student and the faculty supervisor.

PHYS 330. Experimental Methods in Biophysics. 3 Units.
There is an extensive array of powerful and elegant tools used to obtain quantitative and qualitative information about the physics of biology. New, cutting-edge techniques are being developed by labs around the world every day. To solve important problems in biophysics, an understanding of the capabilities and limitations of the current instrumental methods is needed. This course will focus on the physical principles of biophysical instrumentation so that appropriate choices and efficient use of measurement tools can be made. Exposure to instrumentation in core facilities around campus will link lectures to practical demonstrations of the operation of instrumentation. Techniques applied to a diversity of biological macromolecules and assemblies from the molecular level of proteins, nucleic acids, lipids, up to higher organization of cells, cellular organisms and tissues will be discussed. Topics covered include spectroscopic methods (IR/vis/UV/X-ray regions of the electromagnetic spectrum, absorption, fluorescence, circular dichroism, dynamic light scattering, Raman, electron paramagnetic resonance, NMR), microscopy techniques (electron, atomic force, scanning tunneling, optical), separation techniques (sedimentation, centrifugation, chromatography), crystallography, calorimetry, mass spectrometry, single molecule detection, cell sorting, functional genomics and proteomics and laboratory evolution. Biological examples from historical and current literature will be used to demonstrate the merits of each of the methods. Offered as PHYS 330 and PHYS 430. Prereq: PHYS 122 or PHYS 124.

PHYS 331. Introduction to Quantum Mechanics I. 3 Units.
Quantum nature of energy and angular momentum, wave nature of matter, Schroedinger equation in one and three dimensions; matrix methods; Dirac notation; quantum mechanical scattering. Two particle wave functions. Prereq: PHYS 221.

PHYS 332. Introduction to Quantum Mechanics II. 3 Units.
Continuation of PHYS 331. Spin and fine structure; Dirac equation; symmetries; approximation methods; atomic and molecular spectra; time dependent perturbations; quantum statistics; applications to electrons in metals and liquid helium. Prereq: PHYS 331.

PHYS 336. Modern Cosmology. 3 Units.
An introduction to modern cosmology and an exploration of current topics in the field. The first half of the course will cover the mathematical and physical basis of cosmology, while the second will delve into current questions and the observations that constrain them. Offered as PHYS 336 and PHYS 436. Prereq: PHYS 221.

PHYS 339. Seminar. 1 - 3 Units.
Conducted in small sections with presentation of papers by students and informal discussion. Special problem seminars and research seminars offered according to interest and need, often in conjunction with one or more research groups.

PHYS 349. Methods of Mathematical Physics I. 3 Units.
Analysis of complex functions: singularities, residues, contour integration; evaluation and approximation of sums and integrals; exact and approximate solution of ordinary differential equations; transform calculus; Sturm-Liouville theory; calculus of variations. Additional work required for graduate students. Offered as PHYS 349 and PHYS 449. Prereq: (PHYS 121 or PHYS 123) and (MATH 224 or MATH 228).

PHYS 351. Senior Physics Project. 2 Units.
A two semester course required for senior BS and BA physics majors. Students pursue a project based on experimental, theoretical or teaching research under the supervision of a physics faculty member, a faculty member from another CWRU department or a research scientist or engineer from another institution. A departmental Senior Project Committee must approve all project proposals and this same committee will receive regular oral and written progress reports. Final results are presented at the end of the second semester as a paper in a style suitable for publication in a professional journal as well as an oral report in a public symposium. Counts as a SAGES Senior Capstone course. Prereq: PHYS 303. Coreq: PHYS 352.

PHYS 352. Senior Physics Project Seminar. 1 Unit.
This two semester seminar is taken concurrently with the student's two semester senior project. Students meet weekly to discuss their projects and the research experience. The class will include dialogues about professional issues such as ethics, graduate school, jobs, funding, professional organizations, public obligations, writing and speaking. Assignments include proposals, progress reports and posters. Counts as a SAGES Departmental Seminar course. Counts as a SAGES Senior Capstone course. Coreq: PHYS 351 or PHYS 353.

PHYS 353. Senior Engineering Physics Project. 2 Units.
A two semester course required for BSE Engineering Physics majors. Students are expected to complete a research project in their concentration area under the supervision of a faculty member in science, engineering, or, with approval, a researcher at another institution or company. The project may be calculational, experimental or theoretical, and will address both the underlying physics and appropriate engineering and design principles. A program Senior Project Committee must approve all project proposals and will receive regular oral and written progress reports. Final results are presented at the end of the second semester as a paper in a style suitable for publication in a professional journal as well as an oral report in a public symposium. Counts as a SAGES Senior Capstone course. Prereq: PHYS 318. Coreq: PHYS 352.

PHYS 365. General Relativity. 3 Units.
This is an introductory course in general relativity. The techniques of tensor analysis will be developed and used to describe the effects of gravity and Einstein's theory. Consequences of the theory as well as its experimental tests will be discussed. An introduction to cosmology will be given. Additional work required for graduate students. Offered as PHYS 365 and PHYS 465.

PHYS 366. Life after Graduation (Bachelor, Master, and Doctoral). 1 Unit.
This course introduces both undergraduate and graduate students to the many career paths that people can take, and have taken, with physics degrees (Bachelor, Master, and Doctoral). The majority of physics graduates, including BS, MS, and PhD, pursue careers outside of academia, and therefore need guidance for non-academic careers. This course is not required for any degree but will provide physics majors and graduate students with opportunities for career exploration, primarily via weekly talks featuring physicists from various industrial and government entities and secondarily through a semester-long set of assignments that centers on creating documents relevant to career paths. Offered as PHYS 366 and PHYS 466.

PHYS 372. Instrumentation and Physics Laboratory. 3 Units.
Students complete a series of projects designed to introduce modern instrumentation and laboratory research techniques. Topics may include low temperature phenomena, nuclear gamma ray detection and measurement, and optics. Students will discuss various issues associated with physics research including judging the quality of experimental data (error analysis), presenting work in written and oral formats, safety concerns in the laboratory, and ethical considerations. Counts as a Disciplinary Communication course.

PHYS 386. Quantum Computing, Information, and Devices. 3 Units.
An introduction to the math, physics, engineering, and computer science underlying the rapidly emerging fields of quantum computing, quantum information, and quantum devices. The course is taught by a group of faculty from physics, engineering, computer science, and math, and is geared towards students with diverse backgrounds and interests in these fields. Students will select a concentration in one of these four areas, and the coursework, while still covering all topics, will be adjusted to focus on the selected area in the most detail. Note that the listed prerequisites depend on choice of concentration. Topics will include: 1. (Mathematics) Introduction to linear algebra, convex geometry, fundamental theory of quantum information. 2. (Physics) Introduction to the quantum mechanics of two-level systems (qubits). Survey of physics and materials for qubit technologies. 3. (Computer Science) Basic quantum gates and circuits, introduction to the theory of algorithms, survey of quantum algorithms. 4. (Engineering) Quantum architectures, mapping algorithms onto circuits. The course consists of lectures, homework, and group projects. Group projects will aim to synthesize the diverse backgrounds of the students and instructors to capture the interdisciplinary nature of the field. Students taking the course for graduate credit will complete an additional literature research project and presentation, in addition to enhanced problem sets. Offered as CSDS 386, CSDS 486, ECSE 386, ECSE 486, MATH 386, MATH 486, PHYS 386, and PHYS 486. Prereq: PHYS 331 and (MATH 223 or MATH 227) and (MATH 224 or MATH 228) and (ENGR 131 or CSDS 132 or ECSE 132) and (PHYS 122 or PHYS 124).

PHYS 390. Undergraduate Research in Physics. 0 - 6 Units.
Research conducted under the supervision of a faculty member in the Department of Physics. Arrangements must be made with a faculty member and a written description of these arrangements must be submitted to and approved by the department before a permit will be issued to register for this course. A final report must be supplied to the department at the end of the semester.

PHYS 413. Classical Mechanics. 3 Units.
An introduction to classical mechanics, Lagrangian and Hamiltonian formulations, conservation laws, kinematics and dynamics, Poisson brackets, Liouville Theorem, canonical transformation, and action angle variables. To be followed by PHYS 414.

PHYS 414. Foundations of Statistical Mechanics. 3 Units.
Noninteracting systems, statistical mechanics of solids, liquids, gases, fluctuations, irreversible processes, phase transformations. Statistical mechanics provides a set of universal principles to describe the physics of complex systems, irrespective of their microscopic details. This course is a self-contained introduction to the mathematical foundations of the subject, starting from basic concepts of probability and the dynamics of classical systems in phase space, covering topics like ergodicity, chaos, and master equations. Using this framework we systematically derive the laws of equilibrium thermodynamics and show how they are a limiting case of recently discovered fluctuation theorems that are valid arbitrarily far from equilibrium. Along the way we explore the many facets and consequences of these laws: entropy as information, universal bounds on the efficiency of engines, the fluctuation-dissipation relation and Onsager reciprocity. Finally, we connect these ideas to the quantum realm, via the physics of decoherence and quantum master equations. The course is open to students from all backgrounds who have basic familiarity with undergraduate classical and quantum physics (a previous statistical mechanics course is helpful but not necessary). Examples in class and in the problem sets highlight the broad interdisciplinary scope of statistical mechanics, from biophysics to machine learning to quantum information.

PHYS 415. Introduction to Solid State Physics. 3 Units.
Characterization and properties of solids; crystal structure, thermal properties of lattices, quantum statistics, electronic structure of metals and semiconductors. PHYS 415 for graduate students in engineering and science. (May not be taken for departmental credit by graduate students in the Department of Physics.) Prerequisite may be waived with consent of department. Recommended preparation for PHYS 415: PHYS 331. Offered as PHYS 315 and PHYS 415. Prereq: Graduate standing.

PHYS 420. Introduction to Biological Physics. 3 Units.
This course explores the intersection of physics and biology: how do fundamental physical laws constrain life processes inside the cell, shaping biological organization and dynamics? We will start at the molecular level, introducing the basic ideas of nonequilibrium statistical physics and thermodynamics required to describe the fluctuating environment of the cell. This allow us to build up a theoretical framework for a variety of elaborate cellular machines: the molecular motors driving cell movement, the chaperones that assist protein folding, the information-processing circuitry of genetic regulatory networks. The emphasis throughout will be on simple, quantitative models that can tackle the inherent randomness and variability of cellular phenomena. We will also examine how to verify these models through the rich toolbox of biophysical experimental and computational technologies. The course should be accessible to students from diverse backgrounds in the physical and life sciences: we will explain both the biological details and develop the necessary mathematical / physical ideas in a self-contained manner. Offered as PHYS 320 and PHYS 420. Prereq: Graduate student standing.

PHYS 421. Advanced Computational Methods in Physics. 3 Units.
Advanced numerical methods applied to physical problems. Use of personal computers in the solution of practical problems encountered in physics. Topics may include ordinary and partial differential equations, linear algebra, and Monte Carlo techniques. Focus is placed on developing, documenting, testing, and presenting solutions to physical problems. Standard, collaborative tools commonly used in research groups will be employed. Offered as PHYS 321 and PHYS 421.

PHYS 423. Classical Electromagnetism. 3 Units.
Electromagnetic theory in the classical limit. Gauge invariance and special relativity. Applications to electrostatic, magnetostatic, and radiation problems using advanced mathematical techniques. Dielectric, magnetic, and conducting materials. Wave propagation in open and confined geometries. Radiation from accelerating charges. Cherenkov, synchrotron, and transition radiation.

PHYS 426. Physical Optics. 3 Units.
Geometrical optics and ray tracing, wave propagation, interaction of electromagnetic radiation with matter, interference, diffraction, and coherence. Supplementary current topics from modern optics such as nonlinear optics, holography, optical trapping and optical computing. Prerequisite(s) may be waived with consent of department. Offered as PHYS 326 and PHYS 426. Prereq: Graduate standing.

PHYS 427. Laser Physics. 3 Units.
An introduction to theoretical and practical quantum electronics covering topics in quantum optics, laser physics, and nonlinear optics. Topics to be addressed include the physics of two-level quantum systems including the density matrix formalism, rate equations, and semiclassical radiation theory; laser operation including oscillation, gain, resonator optics, transverse and longitudinal modes, Q-switching, mode-locking, and coherence; and nonlinear optics including the nonlinear susceptibility, parametric interactions, stimulated processes, and self-action. Recommended preparation for PHYS 427: PHYS 331 or PHYS 481. Offered as PHYS 327 and PHYS 427. Prereq: Graduate standing.

PHYS 428. Cosmology and the Structure of the Universe. 3 Units.
Distances to galaxies. The content of the distant universe. Large scale structure and galaxy clusters. Physical cosmology. Structure and galaxy formation and evolution. Testing cosmological models. Offered as ASTR 328, PHYS 328, ASTR 428, and PHYS 428.

PHYS 430. Experimental Methods in Biophysics. 3 Units.
There is an extensive array of powerful and elegant tools used to obtain quantitative and qualitative information about the physics of biology. New, cutting-edge techniques are being developed by labs around the world every day. To solve important problems in biophysics, an understanding of the capabilities and limitations of the current instrumental methods is needed. This course will focus on the physical principles of biophysical instrumentation so that appropriate choices and efficient use of measurement tools can be made. Exposure to instrumentation in core facilities around campus will link lectures to practical demonstrations of the operation of instrumentation. Techniques applied to a diversity of biological macromolecules and assemblies from the molecular level of proteins, nucleic acids, lipids, up to higher organization of cells, cellular organisms and tissues will be discussed. Topics covered include spectroscopic methods (IR/vis/UV/X-ray regions of the electromagnetic spectrum, absorption, fluorescence, circular dichroism, dynamic light scattering, Raman, electron paramagnetic resonance, NMR), microscopy techniques (electron, atomic force, scanning tunneling, optical), separation techniques (sedimentation, centrifugation, chromatography), crystallography, calorimetry, mass spectrometry, single molecule detection, cell sorting, functional genomics and proteomics and laboratory evolution. Biological examples from historical and current literature will be used to demonstrate the merits of each of the methods. Offered as PHYS 330 and PHYS 430.

PHYS 431. Physics of Imaging. 3 Units.
Description of physical principles underlying the spin behavior in MR and Fourier imaging in multi-dimensions. Introduction of conventional, fast, and chemical-shift imaging techniques. Spin echo, gradient echo, and variable flip-angle methods. Projection reconstruction and sampling theorems. Bloch equations, T1 and T2 relaxation times, rf penetration, diffusion and perfusion. Flow imaging, MR angiography, and functional brain imaging. Sequence and coil design. Prerequisite may be waived with consent of instructor. Recommended preparation: PHYS 122 or PHYS 124 or EBME 410. Offered as EBME 431 and PHYS 431.

PHYS 436. Modern Cosmology. 3 Units.
An introduction to modern cosmology and an exploration of current topics in the field. The first half of the course will cover the mathematical and physical basis of cosmology, while the second will delve into current questions and the observations that constrain them. Offered as PHYS 336 and PHYS 436. Prereq: Graduate standing.

PHYS 441. Physics of Condensed Matter I. 3 Units.
Crystal structure, x-ray diffraction, band theory and applications. Free electron theory of metals and electrons in magnetic fields.

PHYS 442. Physics of Condensed Matter II. 3 Units.
Continuation of PHYS 441. Lattice vibrations, thermal properties of solids, semiconductors, magnetic properties of solids, and superconductivity. Prerequisite may be waived with consent of department. Recommended preparation: PHYS 441.

PHYS 449. Methods of Mathematical Physics I. 3 Units.
Analysis of complex functions: singularities, residues, contour integration; evaluation and approximation of sums and integrals; exact and approximate solution of ordinary differential equations; transform calculus; Sturm-Liouville theory; calculus of variations. Additional work required for graduate students. Offered as PHYS 349 and PHYS 449. Prereq: Graduate standing.

PHYS 451. Empirical Foundations of the Standard Model. 3 Units.
The experimental basis for modeling the electroweak and strong interactions in terms of fundamental fermions, quarks and leptons, and gauge bosons, photons, the weak bosons, and gluons; particle accelerators and detection techniques; phenomenology of particle reactions, decays and hadronic structure; space, time and internal symmetries; symmetries; symmetry breaking.

PHYS 460. Advanced Topics in NMR Imaging. 3 Units.
Frontier issues in understanding the practical aspects of NMR imaging. Theoretical descriptions are accompanied by specific examples of pulse sequences, and basic engineering considerations in MRI system design. Emphasis is placed on implications and trade-offs in MRI pulse sequence design from real-world versus theoretical perspectives. Recommended preparation: EBME 431 or PHYS 431. Offered as EBME 460 and PHYS 460. Prereq: Graduate standing or Undergraduate with Junior or Senior standing and a cumulative GPA of 3.2 or above.

PHYS 465. General Relativity. 3 Units.
This is an introductory course in general relativity. The techniques of tensor analysis will be developed and used to describe the effects of gravity and Einstein's theory. Consequences of the theory as well as its experimental tests will be discussed. An introduction to cosmology will be given. Additional work required for graduate students. Offered as PHYS 365 and PHYS 465. Prereq: Graduate standing.

PHYS 466. Life after Graduation (Bachelor, Master, and Doctoral). 1 Unit.
This course introduces both undergraduate and graduate students to the many career paths that people can take, and have taken, with physics degrees (Bachelor, Master, and Doctoral). The majority of physics graduates, including BS, MS, and PhD, pursue careers outside of academia, and therefore need guidance for non-academic careers. This course is not required for any degree but will provide physics majors and graduate students with opportunities for career exploration, primarily via weekly talks featuring physicists from various industrial and government entities and secondarily through a semester-long set of assignments that centers on creating documents relevant to career paths. Offered as PHYS 366 and PHYS 466. Prereq: Graduate standing.

PHYS 472. Graduate Physics Laboratory. 3 Units.
A series of projects designed to introduce the student to modern research techniques such as automated data acquisition. Students will be assessed as to their individual needs and a sequence of projects will be established for each individual. Topics may include low temperature phenomena, nuclear gamma ray detection and measurement and optics. Prereq; Graduate student standing or Undergraduate student with a Mathematics and Physics major.

PHYS 481. Quantum Mechanics I. 3 Units.
Quantum mechanics with examples of applications. Schroedinger method; matrix and operator methods. Approximation methods including WKB, variational and various perturbation methods. Applications to atomic, molecular and nuclear physics including both bound states and scattering problems. Applications of group theory to quantum mechanics.

PHYS 482. Quantum Mechanics II. 3 Units.
Continuation of PHYS 481, including quantum field theory. Prerequisite may be waived with consent of department. Recommended preparation: PHYS 481 or consent of department.

PHYS 486. Quantum Computing, Information, and Devices. 3 Units.
An introduction to the math, physics, engineering, and computer science underlying the rapidly emerging fields of quantum computing, quantum information, and quantum devices. The course is taught by a group of faculty from physics, engineering, computer science, and math, and is geared towards students with diverse backgrounds and interests in these fields. Students will select a concentration in one of these four areas, and the coursework, while still covering all topics, will be adjusted to focus on the selected area in the most detail. Note that the listed prerequisites depend on choice of concentration. Topics will include: 1. (Mathematics) Introduction to linear algebra, convex geometry, fundamental theory of quantum information. 2. (Physics) Introduction to the quantum mechanics of two-level systems (qubits). Survey of physics and materials for qubit technologies. 3. (Computer Science) Basic quantum gates and circuits, introduction to the theory of algorithms, survey of quantum algorithms. 4. (Engineering) Quantum architectures, mapping algorithms onto circuits. The course consists of lectures, homework, and group projects. Group projects will aim to synthesize the diverse backgrounds of the students and instructors to capture the interdisciplinary nature of the field. Students taking the course for graduate credit will complete an additional literature research project and presentation, in addition to enhanced problem sets. Offered as CSDS 386, CSDS 486, ECSE 386, ECSE 486, MATH 386, MATH 486, PHYS 386, and PHYS 486. Prereq: PHYS 331 and (MATH 223 or MATH 227) and (MATH 224 or MATH 228) and (ENGR 131 or CSDS 132 or ECSE 132) and (PHYS 122 or PHYS 124).

PHYS 491. Modern Physics for Innovation I. 3 Units.
The first half of a two-semester sequence providing an understanding of physics as a basis for successfully launching new high-tech ventures. The course will examine physical limitations to present technologies, and the use of physics to identify potential opportunities for new venture creation. The course will provide experience in using physics for both identification of incremental improvements, and as the basis for alternative technologies. Case studies will be used to illustrate recent commercially successful (and unsuccessful) physics-based venture creation, and will illustrate characteristics for success.

PHYS 492. Modern Physics for Innovation II. 3 Units.
Continuation of PHYS 491, with an emphasis on current and prospective opportunities for Physics Entrepreneurship. Longer term opportunities for Physics Entrepreneurship in emerging areas including, but not limited to, nanoscale physics and nanotechnology; biophysics and applications to biotechnology; physics-based opportunities in the context of information technology. Recommended preparation: PHYS 491.

PHYS 495. Applied Patent Law. 1 Unit.
This course is designed to equip STEM students with practical knowledge of patent law, the patenting process, intellectual property (IP) strategy and IP management. Specific areas of study include: law and policy of patents, requirements to obtain a patent, the anatomy of the patent document, patent portfolio strategies, preparing and filing a patent application, IP management and monetization, managing IP in a research and development environment, sponsored research and service agreements, trade secrets and their relationship to patents, and non-disclosure agreements.

PHYS 539. Special Topics Seminar. 1 - 3 Units.
Individual or small group instruction on topics of interest to the department. Topics include, but are not limited to, particle physics, astrophysics, optics, condensed matter physics, biophysics, imaging. Several such courses may run concurrently.

PHYS 545. Medical Physics Clinical Practicum. 3 Units.
Clinical Practicum is a one-semester required course in the medical physics track of the physics master's degree. It is a series of rotations in radiation oncology, medical diagnostic imaging, and radiation safety/standards, as well as in nuclear medicine. Students observe and obtain introductory hands-on experience pertaining to instrumentation, treatment planning, and quality assurance.

PHYS 595. Applications of Quantum Field Theory in Modern Physics. 3 Units.
Basics elements of Quantum Field Theory, Applications of Quantum Field Theory to condensed matter systems, particle physics and cosmology. Strong, Weak and Electromagnetic Forces, Two-dimensional (2D) condensed matter systems, Neutrino Oscillations, The Dark Matter Problem. Prereq: PHYS 481.

PHYS 601. Research in Physics. 1 - 9 Units.

PHYS 651. Thesis M.S.. 1 - 9 Units.
(Credit as arranged.)

PHYS 666. Frontiers in Physics. 0 Unit.
Weekly colloquia given by eminent physicists from around the world on topics of current interest in physics.

PHYS 701. Dissertation Ph.D.. 1 - 9 Units.
(Credit as arranged.) Prereq: Predoctoral research consent or advanced to Ph.D. candidacy milestone.