PHYSICS (PHYS)

* **PHYS 123Lb / MB&B 1230Lb / PHYS 1230Lb and PHYS 123Lb, Introduction to Physics in Living Systems III: Mechanics** Andrew Miranker
A hands-on introduction to the physics that enables life and human measurement of living things. The course focuses on the principles of mechanics at work in the biological sciences. This lab builds student knowledge, centering diffusion as an emergent phenomenon from elastic collisions, from which statistical mechanics is introduced. For students choosing to major in MB&B, this course may be used to fulfill the MB&B requirement for *Practical Skills* in physics. Priority for this 1/2 credit course is given to first-year students looking to fulfill medical school application requirements. It is helpful to take this course in the same semester as MB&B 124L. ½ Course cr

* **PHYS 0400a / ASTR 0400a, Expanding Ideas of Time and Space** Meg Urry
Discussions on astronomy, and the nature of time and space. Topics include the shape and contents of the universe, special and general relativity, dark and light matter, and dark energy. Observations and ideas fundamental to astronomers' current model of an expanding and accelerating four-dimensional universe. Enrollment limited to first-year students. SC

* **PHYS 0500a / APHY 0500a / ENAS 0500a, Science of Modern Technology and Public Policy** Daniel Prober
Examination of the science behind selected advances in modern technology and implications for public policy, with focus on the scientific and contextual basis of each advance. Topics are developed by the participants with the instructor and with guest lecturers, and may include nanotechnology, quantum computation and cryptography, renewable energy technologies, optical systems for communication and medical diagnostics, transistors, satellite imaging and global positioning systems, large-scale immunization, and DNA made to order. Enrollment limited to first-year students. SC

* **PHYS 0700a, Nuclear Physics: The Good, The Bad, and the Misunderstood** Helen Caines
This course aims to introduce students to the basics of nuclear radiation and its uses. What exactly is radiation? How do we detect it? How come a little exposure can be good for us but too much deadly? Is nuclear energy a viable option? Is my cell phone dangerous? Should I get that dental x-ray? By the end of the course students are armed with necessary physics insights to answer the above questions and more. No prerequisites are required but completion of a high school physics course, or similar subject is preferred. Enrollment limited to first-year students. SC

* **PHYS 0800b and PHYS 1000b / APHY 0800b and APHY 1000b / ENAS 0800b / EPS 0800b / EVST 0080b and EVST 1000b, Energy, Environment, and Public Policy** Daniel Prober
The technology and use of energy. Impacts on the environment, climate, security, and economy. Application of scientific reasoning and quantitative analysis. Intended for non–science majors with strong backgrounds in math and science. Tours are be conducted of major examples of good energy design at Yale, including the Yale Power Plant and Kroon Hall. Students who take this course are not eligible to take

APHY 100. Prerequisites: High school chemistry, physics, and Math. Calculus is not required. Enrollment limited to first-year students. QR, SC

PHYS 1060a / EVST 2206a / HIST 1727a / HSHM 2010a / HUMS 1060a, Sustainable Energy: Physics and History
Students explore the physical logic of energy and power in parallel with the histories of technology for energy exploitation and economic theories of sustainability on the path to modernity. They learn the fundamentals of quantitative analysis of contemporary and historical energy harvesting, its carbon intensity, and climate impact. They also gain an understanding of the historical underpinnings of the current global energy status quo and its relationship to economic theories of sustainability. Mathematical proficiency with algebra is assumed. Students from all academic interests and experiences are welcome in the course. QR, SC, SO 0 Course cr

* **PHYS 1070b / EDST 107 / EDST 3107b / MB&B 1070b, Being Human in STEM** Staff
A collaboratively designed, project-oriented course that seeks to examine, understand, and disseminate how diversity of gender, race, religion, sexuality, economic circumstances, etc. shape the STEM experience at Yale and nationally, and that seeks to formulate and implement solutions to issues that are identified. Study of relevant peer-reviewed literature and popular-press articles. OpEd writing project and design and implementation of an intervention project focusing on improving belonging in Yale STEM communities. SO

* **PHYS 1200b, Quantum Physics and Beyond** Staff
Current topics in modern physics, beginning with quantum physics and continuing through subatomic physics, special and general relativity, cosmology, astrophysics, and string theory. SC

* **PHYS 1210La / MB&B 1210La, Introduction to Physics in Living Systems I: Observation and Analysis** Staff
A hands-on introduction to the physics that enables life and human measurement of living things. This lab builds student knowledge of scientific experimental design and practice. Topics include detection of light, basic circuit building, sterile technique in biology and physics, data collection with student-built instrumentation, and quantitative assessment. For students choosing to major in MB&B, this course may be used to fulfill the MB&B requirement for *Practical Skills* in physics. There are no prerequisites to this ½ credit class and it is helpful to take it in the same semester as MB&B 122L. Priority is given to first-year students looking to fulfill medical school application requirements and students seeking to join research labs at Yale. SC 0 Course cr

* **PHYS 1220La / MB&B 1220La, Introduction to Physics in Living Systems: Observation and Analysis II** Staff
A hands-on introduction to the physics that enables life and human measurement of living things. This lab builds student knowledge of scientific experimental design and practice, focusing on building models from experimental data. Topics included electrical circuits, magnetism, data collection with student-built instrumentation, and quantitative assessment. For students choosing to major in MB&B, this course may be used to fulfill the MB&B requirement for Practical Skills in physics. Previously MB&B 122L. Taking MB&B/PHYS 1210L before this class is required, as the material builds on

itself. Priority is given to first-year students looking to fulfill medical school application. 0 Course cr

*** PHYS 1230Lb and PHYS 123Lb / MB&B 1230Lb, Introduction to Physics in Living Systems III: Mechanics** Andrew Miranker
A hands-on introduction to the physics that enables life and human measurement of living things. The course focuses on the principles of mechanics at work in the biological sciences. This lab builds student knowledge, centering diffusion as an emergent phenomenon from elastic collisions, from which statistical mechanics is introduced. For students choosing to major in MB&B, this course may be used to fulfill the MB&B requirement for *Practical Skills* in physics. Priority for this 1/2 credit course is given to first-year students looking to fulfill medical school application requirements. It is helpful to take this course in the same semester as MB&B 124L. ½ Course cr per term

*** PHYS 1240Lb / MB&B 1240Lb, Introduction to Physics in Living Systems Laboratory IV: Electricity, Magnetism, and Radiation** Andrew Miranker
Introduction to the physics that enables life and human measurement of living things. This lab introduces principles of electricity, magnetism, light and optics at work in the biological sciences. The syllabus emphasizes electric dipoles as a model for biomolecules, electric fields such as those across cell membranes, electric current, and magnetic fields. Light is developed in terms of electromagnetic radiation, ray optics and photons. The interaction of light with biomolecules to understand basic biological research and medical diagnostics are also covered. For students choosing to major in MB&B, this course may be used to fulfill the MB&B requirement for *Practical Skills* in physics. There are no prerequisites to this ½ credit class and it is helpful to take it in the same semester as MB&B 123L. May not be taken after PHYS 166L. Priority is given to first-year students looking to fulfill medical school application requirements and students seeking to join research labs at Yale. SC 0 Course cr

PHYS 1510a or b / APHY 1510a or b / ENAS 1510a or b, Multivariable Calculus for Engineers Staff
An introduction to multivariable calculus focusing on applications to engineering problems. Topics include vector-valued functions, vector analysis, partial differentiation, multiple integrals, vector calculus, and the theorems of Green, Stokes, and Gauss. Prerequisite: MATH 115 or equivalent. QR

PHYS 1650La and PHYS 1660Lb, General Physics Laboratory Staff
A variety of individually self-contained experiments are roughly coordinated with the lectures in PHYS 170, 171, and 180, 181 and illustrate and develop physical principles covered in those lectures. SC 0 Course cr per term

*** PHYS 1700a and PHYS 1710b, University Physics for the Life Sciences** Staff
An introduction to classical physics with special emphasis on applications drawn from the life sciences and medicine. Fall-term topics include vectors and kinematics, Newton's laws, momentum, energy, random walks, diffusion, fluid mechanics, mathematical modeling, and statistical mechanics. Spring-term topics include oscillations, waves, sound, electrostatics, circuits, Maxwell's equations, electromagnetic waves, gene circuits, and quantum mechanics. Essential mathematics are introduced and explained as needed. Completion of MATH 112 or equivalent is prerequisite for PHYS 170. Completion of PHYS 170 is a prerequisite for PHYS 171. MATH 116

(or MATH 115) is recommended prior to or concurrently with PHYS 171. QR, SC
0 Course cr per term

PHYS 1800a and PHYS 1810b, University Physics Staff
A broad introduction to classical and modern physics for students who have some previous preparation in physics and mathematics. Fall-term topics include Newtonian mechanics, gravitation, waves, and thermodynamics. Spring-term topics include electromagnetism, special relativity, and quantum physics. Concurrently with MATH 115 and 120 or equivalents. See comparison of introductory sequences and laboratories in the YCPS. May not be taken for credit after PHYS 170, 171. QR, SC

PHYS 2000a and PHYS 2010b, Fundamentals of Physics Staff
A thorough introduction to the principles and methods of physics for students who have good preparation in physics and mathematics. Emphasis on problem solving and quantitative reasoning. Fall-term topics include Newtonian mechanics, special relativity, gravitation, thermodynamics, and waves. Spring-term topics include electromagnetism, geometrical and physical optics, and elements of quantum mechanics. Prerequisite: MATH 115 or equivalent. MATH 120 and either MATH 225 or MATH 222, are generally taken concurrently. See comparison of introductory sequences and laboratories in the YCPS. QR, SC

PHYS 2050La or b and PHYS 2060La or b, Modern Physical Measurement Staff
A two-term sequence of experiments in classical and modern physics for students who plan to major in Physics. In the first term, the basic principles of mechanics, electricity, and magnetism are illustrated in experiments designed to make use of computer data handling and teach error analysis. In the second term, students plan and carry out experiments illustrating aspects of wave and quantum phenomena and of atomic, solid state, and nuclear physics using modern instrumentation. May be begun in either term. SC 0 Course cr per term

* **PHYS 2600a and PHYS 2610b, Intensive Introductory Physics** Staff
An introduction to major branches of physics—classical and relativistic mechanics; gravitation; electricity and magnetism; and quantum physics,information, and computation—at a sophisticated level. For students majoring in the physical sciences, mathematics, and philosophy whose high school training included both mechanics and electricity and magnetism at the typical college/AP level and have excellent training in, and a flair for, mathematical methods and quantitative analysis. Concurrently with MATH 120, ENAS 151, PHYS 151, or PHYS 301, or equivalent. Students considering an alternative MATH course should check with the DUS in Physics. QR, SC

* **PHYS 2710a, Independent Research in Physics** David Poland
Each student works on an independent project under the supervision of a member of the faculty or research staff. Students participate in a series of seminar meetings in which they present a talk on their project or research related to it. A written report is also required. For students with a strong background in physics coursework. This course may be taken multiple times for pass/fail credit. Suggested for first years and sophomores.

PHYS 3200a, Physics and Public Policy Barbara Cruvinel Santiago
Case studies in the science and technology enterprise in the United States and selected foreign countries focused on topics in the physical sciences; how science and technology affect public policy and in turn are affected by it; how research is planned, supported,

evaluated, and utilized; how criteria for selection of research areas are developed and used in the executive and legislative branches of government. *No detailed background in physical science or mathematics required, but some basic understanding might be helpful. Physics concepts will be introduced as needed."* WR, SO

PHYS 3410b, Biological Physics Staff
An introduction to the physics of biological structures and life processes, and to the burgeoning field of biological physics. Related concepts from probability theory and statistical physics are developed as needed. Prerequisite: PHYS 170, 171, or 180, 181, or 200, 201, or 260, 261, or permission of instructor. QR, SC

PHYS 3420a / EPS 3420a, Introduction to Earth and Environmental Physics John Wettlaufer
A broad introduction to the processes that affect the past, present, and future features of the Earth. Examples include climate and climate change and anthropogenic activities underlying them, planetary history, and their relation to our understanding of Earth's present dynamics and thermodynamics. Prerequisite: PHYS 1700, 1710, or 1800, 1810, or 2000, 2010, or 2600, 2610, MATH 1200, 2460, or ENAS 1940, or permission of instructor. QR, SC

PHYS 3450b, Introduction to Quantum Information Processing and Communication Staff
This course is intended for undergraduate physics, chemistry, engineering, computer science, statistics and data science, and mathematics majors seeking an introduction to quantum information science. There is now a second quantum revolution underway and a world-wide race to build powerful new types of computers based on quantum principles, and to develop new techniques for encrypted communication whose security is guaranteed by the laws of quantum mechanics. The approach of this course to these topics will strip away much of the traditional physics details to focus on the information content of quantum systems, the nature of measurement, and why the true randomness of certain measurement results can be a feature rather than a bug. We learn what it means for a quantum bit ('qubit') to be simultaneously 0 and 1 (in some sense). We learn about quantum entanglement and the associated 'spooky action at a distance' that convinced Einstein that the quantum theory must be wrong. Ironically, this bizarre effect is now used on a daily basis to prove that quantum mechanics is indeed correct and used as a routine engineering test to make sure that quantum computers are working properly and are truly quantum. Specific topics include: the mathematical representation of quantum states as complex vectors, the superposition principle, entanglement and Bell inequalities, quantum gates and algorithms for quantum computers, quantum error correction, dense coding, teleportation, and secure quantum communication. Students learn to do problem sets based on programming and operating publicly-accessible cloud-based quantum computers. See for example: https://www.ibm.com/quantum-computing/. Familiarity with complex numbers and the basics of linear algebra (matrices, determinants, eigenvectors and eigenvalues) is assumed. Prior exposure to basic probability and statistics. as well as a course in quantum mechanics are useful but not required. SC

PHYS 3530a / BENG 3500a, Introduction to Biomechanics Michael Murrell
An introduction to the biomechanics used in biosolid mechanics, biofluid mechanics, biothermomechanics, and biochemomechanics. Diverse aspects of biomedical engineering, from basic mechanobiology to the design of novel biomaterials, medical

devices, and surgical interventions. Prerequisites: PHYS 180, PHYS 181, MATH 115, and ENAS 194. QR 0 Course cr

* **PHYS 3560a / ASTR 3560a / ASTR 5560a, Astrostatistics and Data Mining** Earl Bellinger
This course is intended to give students majoring in astronomy, physics, or any other physical science the necessary background to be able to conduct research with large and complex datasets. The course provides an introduction to the tools needed for analyzing large volumes of data and gives students more experience in building codes to analyze to them. The course starts with a review of basic probability and statistics. Students then learn the basics of classical statistical inference, regression and model fitting, Bayesian statistical inference, as well as different data-mining techniques. Coding with the Python programming language. Prerequisite: ASTR 255 or equivalent. QR, SC

* **PHYS 3780a, Introduction to Scientific Computing & Data Science** Daisuke Nagai
This course introduces students to essential computational and data analysis methods and tools and their problem-solving applications. These are skills and knowledge essential for beginning research in the sciences, and are not typically taught in an introductory physics curriculum. The goal here is not completeness across any of these areas, but instead the introduction of the most important and useful skills, concepts, methods, techniques, tools and relevant knowledge for getting started in research in physics. Key learning goals include basic programming in Python, data analysis, modeling, simulations and machine learning, and their applications to problems in physics and beyond. Prerequisites: Introductory physics and familiarity with single variable calculus (basic integration, differentiation, Taylor series, etc). Previous experience in Python programming is not required. Contact instructor if you are unsure about your preparation. SC

PHYS 3930a / APHY 3930a, Einstein and the Birth of Modern Physics A Douglas Stone
The first twenty-five years of the 20th century represent a turning point in human civilization as for the first time mankind achieved a systematic and predictive understanding of the atomic level constituents of matter and energy, and the mathematical laws which describe the interaction of these constituents. In addition, the General Theory of Relativity opened up for the first time a quantitative study of cosmology, of the history of the universe as a whole. Albert Einstein was at the center of these breakthroughs, and also became an iconic figure beyond physics, representing scientist genius engaged in pure research into the fundamental laws of nature. This course addresses the nature of the transition to modern physics, underpinned by quantum and relativity theory, through study of Einstein's science, biography, and historical context. It also presents the basic concepts in electromagnetic theory, thermodynamics and statistical mechanics, special theory of relativity, and quantum mechanics which were central to this revolutionary epoch in science. Prerequisites: Two terms of PHYS 170, 171, or PHYS 180, 181, or PHYS 200, 201, or PHYS 260, 261, or one term of any of these course with permission of instructor. QR, SC

PHYS 3950a / ASTR 2550a, Research Methods in Astrophysics Marla Geha
An introduction to research methods in astronomy and astrophysics. The acquisition and analysis of astrophysical data, including the design and use of ground- and space-based telescopes, computational manipulation of digitized images and spectra, and confrontation of data with theoretical models. Examples taken from current research

at Yale and elsewhere. Use of the Python programming language. Prerequisite: background in high school calculus and physics. No previous programming experience required. QR, SC RP

* **PHYS 3960b, The Impact of the Atom** Staff
Born in secrecy, the power of the atom was revealed to the world over Hiroshima in 1945. Since then, the atom has touched every facet of our lives. This seminar explores issues on how the atom has impacted the world using a multidisciplinary approach. These topics may include the impact of the atom on history, infrastructure, budget, arts and culture, peace and activism, healthcare, energy and climate change, policy, national security, international relations, science, and the future. Weekly assignments are supplemented with movie screenings and guest speakers. Prerequisites: One term of PHYS 170, 171, or PHYS 180, 181, or PHYS 200, 201, or PHYS 260, 261, or permission of instructor. SO

PHYS 4000a, Introduction to Mathematical Methods of Physics David Moore
Topics include multivariable calculus, linear algebra, complex variables, vector calculus, and differential equations. Designed to give accelerated access to 400-level courses by providing, in one term, the essential background in mathematical methods. Recommended to be taken concurrently with PHYS 401 or 410. Prerequisite: PHYS 170, 171, or 180, 181, or 200, 201, or 260, 261, or permission of instructor. QR

PHYS 4010a and PHYS 4020b, Advanced Classical Physics from Newton to Einstein Staff
Advanced physics as the field developed from the time of Newton to the age of Einstein. Topics include mechanics, electricity and magnetism, statistical physics, and thermodynamics. The development of classical physics into a "mature" scientific discipline, an idea that was subsequently shaken to the core by the revolutionary discoveries of quantum physics and relativity. Prerequisite: PHYS 170, 171, or 180, 181, or 200, 201, or 260, 261. Concurrently with PHYS 301 or other advanced mathematics course. QR, SC

PHYS 4100a, Classical Mechanics Yoram Alhassid
An advanced treatment of mechanics, with a focus on the methods of Lagrange and Hamilton. Lectures and problems address the mechanics of particles, systems of particles, and rigid bodies, as well as free and forced oscillations. Introduction to chaos and special relativity. Prerequisite: PHYS 170, 171, or 180, 181, or 200, 201, or 260, 261. Concurrently with PHYS 301 or other advanced mathematics course. QR, SC

PHYS 4120b, Relativity Staff
This course covers special relativity and an introduction to general relativity. A thorough treatment of special relativity, stressing equally conceptual understanding and certain formal aspects. Introduction to general relativity covers curved spaces, Einstein's equations, and some of their solutions. Prerequisite: PHYS 401 or PHYS 410. QR, SC

PHYS 4300b, Electromagnetic Fields and Optics Staff
Electrostatics, magnetic fields of steady currents, electromagnetic waves, and relativistic dynamics. Provides a working knowledge of electrodynamics. Prerequisites: PHYS 301 and 410 or equivalents. QR, SC

PHYS 4390a / APHY 4390a, Basic Quantum Mechanics John Sous
The basic concepts and techniques of quantum mechanics essential for solid-state physics and quantum electronics. Topics include the Schrödinger treatment of the

harmonic oscillator, atoms and molecules and tunneling, matrix methods, and perturbation theory. Prerequisites: PHYS 181 or 201, PHYS 301, or equivalents, or permission of instructor. QR, SC

PHYS 4400a, Quantum Mechanics and Natural Phenomena I Ramamurti Shankar
The first term of a two-term sequence covering principles of quantum mechanics with examples of applications to atomic physics. The solution of bound-state eigenvalue problems, free scattering states, barrier penetration, the hydrogen-atom problem, perturbation theory, transition amplitudes, scattering, and approximation techniques. Prerequisite: PHYS 410 or 401. QR, SC

PHYS 4410b, Quantum Mechanics and Natural Phenomena II Staff
Continuation of PHYS 440. Prerequisite: PHYS 440 and either PHYS 430 or permission of the instructor. QR, SC

PHYS 4420a, Introduction to Nuclear and Elementary Particle Physics Ian Moult
Fundamental concepts in nuclear and particle physics, including the discovery of radioactivity, the Dirac equation, antimatter, Feynman diagrams, hadron resonances, quarks and gluons, fundamental symmetries, the weak interaction, beta decay, quantum chromodynamics, neutrino oscillation, unification, and particle theories for dark matter. Prerequisite: two term courses in quantum mechanics. QR, SC

* **PHYS 4450Lb, Advanced Physics Laboratory** Staff
Laboratory experiments with some discussion of theory and techniques. An advanced course focusing on modern experimental methods and concepts in atomic, optical, nuclear, and condensed matter physics. Intended to prepare students for independent research. For majors in the physical sciences. After or concurrently with PHYS 439 or 440, or with permission of instructor. PHYS 206L WR, SC

PHYS 4480a / APHY 4480a, Solid State Physics I Yu He
The first term of a two-term sequence covering the principles underlying the electrical, thermal, magnetic, and optical properties of solids, including crystal structure, phonons, energy bands, semiconductors, Fermi surfaces, magnetic resonances, phase transitions, dielectrics, magnetic materials, and superconductors. Prerequisites: APHY 322, 439, PHYS 420. QR, SC

PHYS 4490b / APHY 4490b, Solid State Physics II Vidvuds Ozolins
The second term of the sequence described under APHY 448. QR, SC

* **PHYS 4500a / APHY 4200a, Thermodynamics and Statistical Mechanics** Eduardo Higino da Silva Neto
This course is subdivided into two topics. We study thermodynamics from a purely macroscopic point of view and then we devote time to the study of statistical mechanics, the microscopic foundation of thermodynamics. Prerequisites: PHYS 301, 410, and 440 or permission of instructor. QR, SC

PHYS 4580a / APHY 4580a, Principles of Optics with Applications Hui Cao
Introduction to the principles of optics and electromagnetic wave phenomena with applications to microscopy, optical fibers, laser spectroscopy, and nanostructure physics. Topics include propagation of light, reflection and refraction, guiding light, polarization, interference, diffraction, scattering, Fourier optics, and optical coherence. Prerequisite: PHYS 430. QR, SC

* **PHYS 4710a, Independent Projects in Physics** David Poland
Each student works on an independent project under the supervision of a member of the faculty or research staff. Students participate in a series of seminar meetings in which they present a talk on their project or research related to it. A written report is also required. Registration is limited to junior and senior physics majors. This course may be taken up to four times for a letter grade.