PHYSICS AND ASTRONOMY

College of Science and Engineering

Dean: Dr. Carmen Domingo

Department of Physics and Astronomy

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Chair: Dr. Joseph Barranco
Graduate Coordinators: Dr. Adrienne Cool (Astronomy) and Dr. Maarten Golterman (Physics)

Mission Statement & Program Scope

The fields of physics & astronomy use the scientific method to investigate the fundamental laws that govern the cosmos and all its contents, from subatomic particles to the cosmic web of galaxies on the largest observable scales in the universe and beyond. The pursuit of science is a human endeavor, and our department welcomes the full spectrum of humanity to contribute their perspectives, passions, and skills to scientific exploration. The mission of San Francisco State University's Department of Physics & Astronomy is to equip students from all backgrounds with foundational content knowledge in classical mechanics, electricity & magnetism, special & general relativity, thermodynamics & statistical mechanics, quantum mechanics, and astronomy & astrophysics; to provide "hands-on" training in theoretical, experimental, observational, and computational techniques for pure research and industrial and "real-world" applications; to mentor students to embrace an empirical, scientific framework to expand the boundaries of knowledge through novel research, and, ultimately, to create diverse STEM leaders, teachers, and policy-makers ready to tackle the most challenging problems facing society locally and globally.

Our department currently offers the following degrees: B.A. Physics (with and without a concentration in Astronomy), B.S. Physics (with and without concentrations in Astrophysics and Physics for Teaching), and M.S. Physics (with and without a concentration in Astronomy). The B.A. degrees are ideal for students who want a strong background in physical science but desire more flexibility to blend their curriculum with other interests. Students with the B.A. degree often pursue careers in teaching, science communication & outreach, pre-medical/dental/health, or business sub-fields in which a rigorous scientific background is beneficial. The B.S. degrees require more in-depth technical training, advanced laboratory experiences, and specialized elective topics. Students with the B.S. degree often pursue science and engineering careers and/or pursue advanced graduate degrees. The B.S. Physics, Concentration in Physics for Teaching allows for a very flexible curriculum that can be combined with Mathematics, Chemistry, or Earth & Climate Sciences to provide breadth across the physical sciences ideal for future K-12 teachers. Our M.S. programs offer the greatest technical depth and usually involve independent research using advanced theoretical, experimental, observational, and computational techniques.

Program Learning Outcomes

Graduates with degrees in Physics & Astronomy will be able to:

a. Describe universal physical principles in classical mechanics, electricity & magnetism, special & general relativity, thermodynamics & statistical mechanics, quantum mechanics, astronomy & astrophysics, and relate fundamental conservation principles (conservation of energy, conservation of linear momentum, conservation of angular momentum) to underlying symmetries of nature.
b. Analyze real-world physical systems on Earth and throughout the Universe, develop simplified models of such systems, translate physical principles into the language of mathematics, and then apply the appropriate mathematical tools (vector calculus, linear algebra, differential equations, variational techniques, probability & statistics, numerical & computational methods) to determine a system's spatiotemporal evolution with an awareness of the limitations of any solutions due to the approximations of the physical models and/or mathematical/computational techniques.
c. Demonstrate proficiency with basic laboratory skills and experimental techniques with electronics, lasers & optical devices, sensors, detectors, microscopes, and telescopes, always with appropriate safety practices (especially with respect to lasers, chemicals, radioactive materials).
d. Articulate and apply the "scientific method," the empirical, iterative method of acquiring new knowledge through developing models to explain observations of the natural world, formulating testable hypotheses, designing and executing experimental, computational, and theoretical investigations to test predictions, analyzing data with appropriate statistics and attention to uncertainties, ascertaining consistency with existing theories, and sharing results with the broader scientific community for confirmation and validation.
e. Demonstrate writing, speaking, and visual data presentation skills to effectively communicate science at the appropriate level of sophistication for the relevant target audience (e.g., instructors, students, scientists, public-at-large, policy-makers).
f. Develop the social and communication skills to effectively participate in diverse scientific teams, including those that are multidisciplinary and/or interdisciplinary, and appreciate that the pursuit of science is a human endeavor and that progress is best made when the full spectrum of humanity is encouraged to participate and share their perspectives, passions, and skills.
g. Engage local, state, national & global communities to address current and emerging scientific and technological challenges in equitable and environmentally sustainable ways.

Professor

Joseph A. Barranco (2007), *Professor in Physics and Astronomy*. Ph.D. University of California, Berkeley.

Kimberly A. Coble (2016), *Professor in Physics and Astronomy*. Ph.D. University of Chicago.

Adrienne Cool (1996), *Professor in Physics and Astronomy*. Ph.D. Harvard University.

Maarten Golterman (2001), *Professor in Physics*. Ph.D. University of Amsterdam.

Jeffrey P. Greensite (1984), *Professor in Physics*. Ph.D. University of California, Santa Cruz.

Weining Man (2008), *Professor in Physics*. Ph.D. Princeton University.

Ronald Marzke (2000), *Professor in Physics and Astronomy*. Ph.D. Harvard University.

Huizhong Xu (2016), *Professor in Physics*. Ph.D. University of Maryland, College Park.

Associate Professor

John M. Brewer (2019), *Associate Professor in Physics and Astronomy*. Ph.D. Yale University.

Charli Sakari (2019), *Associate Professor in Physics and Astronomy*. Ph.D. University of Victoria.

Assistant Professor

Eileen Gonzales (2023), *Assistant Professor in Physics and Astronomy*. Ph.D. The Graduate Center of The City University of New York.

Oscar Macías (2023), *Assistant Professor in Physics and Astronomy*. Ph.D. University of Canterbury.

Adjunct Professor

Debra Fischer (2003), *Adjunct Professor in Physics and Astronomy*. Ph.D. University of California, Santa Cruz.

Adjunct Assistant Professor

Chris McCarthy (2005), *Adjunct Assistant Professor in Physics and Astronomy*. Ph.D. University of California, Los Angeles.

Lecturer Faculty

Dr. Salma Begum, Dr. Jeanne Digel, Jessica Fielder, Violeta Grigorescu, Arefa Hossain, Katie Kooistra, Dr. Elaine Tennant, Aaron White, Dr. Polin Yadak

Majors

- Bachelor of Arts in Physics (http://bulletin.sfsu.edu/colleges/science-engineering/physics-astronomy/ba-physics/)
- Bachelor of Arts in Physics: Concentration in Astronomy (http://bulletin.sfsu.edu/colleges/science-engineering/physics-astronomy/ba-physics-concentration-astronomy/)
- Bachelor of Science in Physics (http://bulletin.sfsu.edu/colleges/science-engineering/physics-astronomy/bs-physics/)
- Bachelor of Science in Physics: Concentration in Astrophysics (http://bulletin.sfsu.edu/colleges/science-engineering/physics-astronomy/bs-physics-concentration-astrophysics/)
- Bachelor of Science in Physics: Concentration in Physics for Teaching (http://bulletin.sfsu.edu/colleges/science-engineering/physics-astronomy/bs-physics-concentration-physics-for-teaching/)

Minors

- Minor in Astronomy (http://bulletin.sfsu.edu/colleges/science-engineering/physics-astronomy/minor-astronomy/)
- Minor in Physics (http://bulletin.sfsu.edu/colleges/science-engineering/physics-astronomy/minor-physics/)

Masters

- Master of Science in Astronomy & Astrophysics (http://bulletin.sfsu.edu/colleges/science-engineering/physics-astronomy/ms-astronomy-astrophysics/)
- Master of Science in Physics (http://bulletin.sfsu.edu/colleges/science-engineering/physics-astronomy/ms-physics/)

Physics Courses (p. 4)

Astronomy

ASTR 115 Introduction to Astronomy (Units: 3)
Prerequisite: Category I or II placement for QR/Math, or completion of GE Area B4, or MATH 197.

Introduction to topics in astronomy including Stonehenge, the solar system, the sun, stars, and stellar evolution, pulsars, black holes, nebulae; galaxies, quasars, the big bang, the expanding universe, and the search for extraterrestrial life. Includes the opportunity for telescopic observation.
Course Attributes:

- B1: Physical Science

ASTR 116 Astronomy Laboratory (Unit: 1)
Prerequisite: ASTR 115 (may be taken concurrently).

Fundamentals of astronomical observation including optics and spectroscopy. Planetarium exploration of the stars, sun, and moon. Opportunity for telescopic observation. Laboratory.
Course Attributes:

- B3: Lab Science

ASTR 300 Stars, Planets, and the Milky Way (Units: 3)
Prerequisite: PHYS 121 or PHYS 230 or PHYS 240 with a grade of C or better.

Quantitative study of stars, stellar evolution, and the Milky Way with an emphasis on the observational basis of our knowledge of the Galaxy's structure and contents. Application of Newton's laws to exoplanets, determination of stellar masses, and evidence for dark matter.

ASTR 301 Observational Astronomy Laboratory (Units: 2)
Prerequisites: ASTR 115 or ASTR 300; and PHYS 121 or PHYS 230 or PHYS 240; all with grades of C or better.

Introduction to observational astronomy, including the celestial sphere & coordinate systems on the sky; apparent motions of the Sun, stars, and planets, astronomical magnitudes, astronomical systems of time, using binoculars & telescopes, geometric optics & telescope design, telescope mounts, limitations of telescope observations, astronomical detectors, photometry, spectroscopy. Lecture, 1 unit; laboratory, 1 unit.

ASTR 340GW The Big Bang - GWAR (Units: 3)
Prerequisites: GE Area A2 and PHYS 320 with a grade of C- or better.

Introduction to cosmology from earlier human conceptions of the universe through the hot Big Bang. Topics include: measuring space and time, the cosmic distance ladder, gravitation, general relativity and the curvature of spacetime, expansion of the universe, large scale structure, the early universe, the cosmic microwave background, nucleosynthesis, dark matter, dark energy and the ultimate fate of the universe. Emphasis will be on how we know what we know about the universe, including observational and experimental evidence. (ABC/NC grading only)
Course Attributes:

- Graduation Writing Assessment

ASTR 400 Stellar Astrophysics (Units: 3)
Prerequisite for ASTR 700: Graduate standing or permission of the instructor.
Prerequisites for ASTR 400: Upper-division standing; ASTR 300, CSC 309 or MATH 209, MATH 245 or MATH 376, and PHYS 320, all with grades of C- or better; GPA of 3.0 or higher; or permission of the instructor.

Introduction to stellar astrophysics: the birth, life, and death of stars, stellar atmospheres and spectra, stellar interiors, energy generation and transport, star formation, stellar evolution and death, the Solar Cycle, and the Sun-Earth connection. (ASTR 700/ASTR 400 is a paired course offering. Students who complete the course at one level may not repeat the course at the other level.)

ASTR 405 Exoplanetary Science (Units: 3)
Prerequisites: PHYS 230 and PHYS 240 with grades of C or better; ASTR 300 with a grade of C- or better (may be taken concurrently).

Study of extra-solar planets including history, detection methods, planet formation, and exoplanetary atmospheres. Exploration of statistics of exoplanetary systems, habitability, and placing the Solar System in a larger context.

ASTR 470 Observational Techniques in Astronomy (Units: 3)
Prerequisites: ASTR 301 and ASTR 300 (may be taken concurrently) with a grade of C- or better; CSC 309 recommended.

Astronomical instrumentation and data analysis with a focus on statistical analysis, CCDs, photometry, spectroscopy, image processing, and instrument design. Lecture, 2 units; laboratory, 1 unit.

ASTR 498 Astronomy Research Literature (Units: 3)
Prerequisite for ASTR 798: Graduate standing or permission of the instructor.
Prerequisites for ASTR 498: Upper-division standing; ASTR 300 and PHYS 320 with grades of C- or better; GPA of 3.0 or higher; or permission of the instructor.

Critical reading and analysis of current peer-reviewed literature in astronomy and astrophysics. Learn about the goals and organization of scientific papers and strategies for reading papers; how to effectively search for and find peer-reviewed publications in astronomy; how to summarize the importance, techniques, and results of papers; and how to effectively communicate this information. Paper topics will vary each semester.
(ASTR 798/ASTR 498 is a paired course offering. Students who complete the course at one level may not repeat the course at the other level.)

ASTR 685 Projects in the Teaching of Astronomy (Unit: 1)
Prerequisites: ASTR 301 or ASTR 470 with a grade of B or better; permission of the instructor.

Methods for effective student teaching in the SF State Observatory and/or Planetarium. Leading of Observatory Open Nights and the development and/or presentation of Planetarium shows. May be repeated for a total of 3 units. (Students may earn a maximum of 4 units toward the baccalaureate degree for any course(s) numbered 685 regardless of discipline.)

ASTR 697 Senior Project (Units: 1-3)
Prerequisite: Senior standing.

Observational or theoretical projects under the direction of department faculty. A written report of the work accomplished is required. May be repeated for a total of 6 units.

ASTR 699 Independent Study (Units: 1-3)
Prerequisites: Advanced Astronomy and Astrophysics majors and minors; approval of the department and permission of the instructor.

Special study in the laboratory, field, or library under the direction of a faculty member. The student must present a written report of the work accomplished to the faculty member and the department. May be repeated for a maximum of 12 units.

ASTR 700 Stellar Astrophysics (Units: 3)
Prerequisite for ASTR 700: Graduate standing or permission of the instructor.
Prerequisites for ASTR 400: Upper-division standing; ASTR 300, CSC 309 or MATH 209, MATH 245 or MATH 376, and PHYS 320, all with grades of C- or better; GPA of 3.0 or higher; or permission of the instructor.

Introduction to stellar astrophysics: the birth, life, and death of stars, stellar atmospheres and spectra, stellar interiors, energy generation and transport, star formation, stellar evolution and death, the Solar Cycle, and the Sun-Earth connection. (ASTR 700/ASTR 400 is a paired course offering. Students who complete the course at one level may not repeat the course at the other level.)

ASTR 722 Radiative Processes in Astrophysics (Units: 3)
Prerequisite: Graduate standing or permission of instructor.

Fundamentals of radiative transfer; basic theory of radiation fields; radiation from moving charges; relativistic covariance and kinematics; bremsstrahlung; synchrotron radiation; Compton scattering; plasma effects; atomic structure; radiative transitions; molecular structure. Applications include stellar and planetary atmospheres, circumstellar disks, the interstellar medium, galaxies, active galactic nuclei, and the intergalactic medium.

ASTR 742 Galaxies and Cosmology (Units: 3)
Prerequisites: Graduate standing or permission of the instructor.

Formation and evolution of galaxies and large-scale structure. Models of hierarchical structure formation in a universe dominated by dark matter. Observational constraints from the discovery of the expansion of the universe to ongoing experiments probing the nature of dark energy.

ASTR 770 Observational Techniques in Astronomy Research (Units: 3)
Prerequisite: Graduate standing or permission of the instructor.

Astronomical photometry, spectroscopy, and astrometry in the context of research. Statistical analysis, observational research program design, and proposal writing. Seminar, 2 units; laboratory, 1 unit.

ASTR 798 Astronomy Research Literature (Units: 3)
Prerequisite for ASTR 798: Graduate standing or permission of the instructor.
Prerequisites for ASTR 498: Upper-division standing; ASTR 300 and PHYS 320 with grades of C- or better; GPA of 3.0 or higher; or permission of the instructor.

Critical reading and analysis of current peer-reviewed literature in astronomy and astrophysics. Learn about the goals and organization of scientific papers and strategies for reading papers; how to effectively search for and find peer-reviewed publications in astronomy; how to summarize the importance, techniques, and results of papers; and how to effectively communicate this information. Paper topics will vary each semester.
(ASTR 798/ASTR 498 is a paired course offering. Students who complete the course at one level may not repeat the course at the other level.)

ASTR 895 Culminating Project (Units: 3)
Prerequisites: Advancement to Candidacy (ATC) and Proposal for Culminating Experience (PCE) forms must be approved by the Division of Graduate Studies before registration.

Independent and original culminating project in astronomy and astrophysics under faculty supervision leading to written project report and oral defense of the project. Culminating projects could include: development of new teaching/curricular modules, portfolios of science writing/journalism, internships in science museums/planetaria or industrial or national research labs, development of technical reports/manuals for new scientific instruments, etc. (CR/NC, RP)

ASTR 896 Directed Reading in Astronomy and Astrophysics (Units: 1-3)
Prerequisite: Graduate standing.

Readings/tutorials to achieve better understanding of specific topics based on individual student need. Focus on review and integration of core concepts in preparation for the comprehensive oral examination. (Does not count toward MS degree requirements.) (CR/NC grading only)

ASTR 896EXM Culminating Experience Examination (Unit: 0)
Prerequisites: Advancement to Candidacy (ATC) and Proposal for Culminating Experience (PCE) forms must be approved by the Division of Graduate Studies before registration.

Comprehensive oral examination on core topics in astronomy and astrophysics. (CR/NC, RP)

ASTR 897 Research (Units: 1-3)
Prerequisite: Graduate standing.

Independent research under the supervision of faculty. May be repeated. (Plus-minus letter grade, CR/NC, RP)

ASTR 898 Master's Thesis (Units: 3)
Prerequisites: Advancement to Candidacy (ATC) and Proposal for Culminating Experience (PCE) forms must be approved by the Division of Graduate Studies before registration.

Independent and original experimental, observational, theoretical, or computational research in astronomy and astrophysics under faculty supervision leading to written Master's Thesis and oral defense of thesis. (CR/NC, RP)

ASTR 899 Independent Study (Units: 1-3)
Prerequisite: Graduate standing.

Independent study under the supervision of faculty. May be repeated. (Plus-minus letter grade, CR/NC, RP)

Physics

PHYS 101 Conceptual Physics (Units: 3)
Prerequisite: Category I or II placement for QR/Math, or GE Area B4, or MATH 197.

Conceptual introduction to Newton's Laws of Motion, properties of matter and energy, heat, sound, light, electricity, magnetism, and atoms.
Course Attributes:

- B1: Physical Science

PHYS 102 Conceptual Physics Laboratory (Unit: 1)
Prerequisite: Concurrent enrollment in PHYS 101.

Laboratory exercises in basic physics.
Course Attributes:

- B3: Lab Science

PHYS 111 General Physics I (Units: 3)
Prerequisites: MATH 198 or MATH 199 or equivalent with a grade of C-minus or higher. Concurrent enrollment in PHYS 112 required. If pre-calculus was completed in high school, the online Math Preparation for Physics mini-course is required; see the Department of Physics & Astronomy website for details.

Introduction to mechanics, waves, sound, fluids, thermodynamics, with applications to biology, life, and health sciences.
Course Attributes:

- B1: Physical Science

PHYS 112 General Physics I Laboratory (Unit: 1)
Prerequisite: Concurrent enrollment in PHYS 111.

Mechanics, heat, and sound. Extra fee required.
Course Attributes:

- B3: Lab Science

PHYS 121 General Physics II (Units: 3)
Prerequisites: PHYS 111 with a grade of C- or better; concurrent enrollment in PHYS 122.

Introduction to electricity, magnetism, light, optics, atoms, and quantum mechanics, with applications to biology, life, and health sciences.

PHYS 122 General Physics II Laboratory (Unit: 1)
Prerequisite: Concurrent enrollment in PHYS 121.

Light, electricity, magnetism, atoms, and modern physics. Extra fee required.

PHYS 200 Planning for Success as a Physics & Astronomy Major (Unit: 1)
Prerequisite: Restricted to Physics & Astronomy majors & minors.

Introduction to the resources and opportunities available to Physics & Astronomy majors at SF State. Discusses resources for research, scholarships and internships, guidelines for professional conduct, programming, scientific writing, academic integrity, advising, and more. Set goals and develop a plan for completing the degree.

PHYS 220 General Physics with Calculus I (Units: 3)
Prerequisites: MATH 226 with a grade of C or better; concurrent enrollment in PHYS 222; concurrent enrollment in MATH 227 recommended.

Introduction to classical mechanics, including vectors, kinematics in one & two dimensions, Newton's Laws of Motion, force & acceleration, linear momentum & impulse, work & kinetic energy, potential energy & conservation of energy, elastic & inelastic collisions, torque & angular momentum, static equilibrium, fixed-axis rotational dynamics, oscillatory motion, gravitation & planetary motion.
Course Attributes:

- B1: Physical Science

PHYS 222 General Physics with Calculus I Laboratory (Unit: 1)
Prerequisite: Concurrent enrollment in PHYS 220.

Experiments in mechanics. Extra fee required.
Course Attributes:

- B3: Lab Science

PHYS 230 General Physics with Calculus II (Units: 3)
Prerequisites: PHYS 220 and MATH 227 with grades of C or better; concurrent enrollment in PHYS 232; concurrent enrollment in MATH 228 recommended.

Introduction to electricity and magnetism, including electric charge and Coulomb's Law, electric field and Gauss's Law, electric potential and electrical potential energy, capacitance, current and resistance, DC circuits, magnetic force and magnetic field, Biot-Savart Law and Ampere's Law, electromagnetic induction and Faraday's Law, inductance, RLC circuits and AC circuits, electromagnetic waves, and Maxwell's equations.

PHYS 232 General Physics with Calculus II Laboratory (Unit: 1)
Prerequisite: Concurrent enrollment in PHYS 230.

Experiments in electricity and magnetism. Extra fee required.

PHYS 240 General Physics with Calculus III (Units: 3)
Prerequisites: PHYS 220 and MATH 227 with grades of C or better; concurrent enrollment in PHYS 242; concurrent enrollment in MATH 228 recommended.

Introduction to thermodynamics & kinetic theory, properties of solids, liquids & gasses, mechanical waves & sound, electromagnetic waves, geometric optics, interference & diffraction, wave-particle duality & quantum mechanics.

PHYS 242 General Physics with Calculus III Laboratory (Unit: 1)
Prerequisite: Concurrent enrollment in PHYS 240.

Experiments in wave motion, optics, and thermodynamics.

PHYS 305 Physical and Astronomical Approaches to Climate Change Solutions (Units: 3)
Prerequisites: GE Areas A1*, A2*, A3*, B1*, and B4* all with grades of C- or better or permission of the instructor.

An investigation of solutions and adaptations to global warming and climate change. Discussions of Earth's energy budget and the interplay between Earth's surface, its atmosphere, the Sun, and human civilization. An introduction to technical solutions related to electricity generation, transportation, heating and cooling, manufacturing, and agriculture. Discussions of geoengineering and the ethical and physical consequences, as well as the impossibility of leaving Earth and traveling to a Planet B to escape climate change. Emphasis on developing personal and community-based action plans for the future. Designed for non-science majors.
Course Attributes:

- UD-B: Physical Life Science
- Environmental Sustainability

PHYS 320 Modern Physics I (Units: 3)
Prerequisites: MATH 228, PHYS 230, and PHYS 240 with grades of C or better; MATH 245 or MATH 376 with a grade of C or better (may be taken concurrently).

Introduction to special relativity and quantum mechanics, including blackbody radiation, photoelectric effect, Compton effect, Bohr model of the hydrogen atom, wave-particle duality, wavefunctions, Heisenberg uncertainty principle, Schrödinger equation, one-dimensional potentials.

PHYS 321 Modern Physics Laboratory (Units: 2)
Prerequisite: Concurrent enrollment in PHYS 320.

Experiments on quantum physics and other phenomena of modern physics. Methods of data and error analysis. Classwork, 1 unit; laboratory, 1 unit.

PHYS 325 Modern Physics II (Units: 3)
Prerequisite: PHYS 320 with a grade of C- or better.

Physics of multi-electron atoms including L and S coupling schemes and optical spectra; elementary concepts of nuclear and elementary particle physics; use of four-vectors to analyze particle collisions and decays.

PHYS 330 Analytical Mechanics I (Units: 3)
Prerequisites: PHYS 230, PHYS 240, and MATH 228, and either MATH 245 or both MATH 225 & MATH 376, all completed with grades of C or better; MATH 376 (may be taken concurrently).

Intermediate course in classical mechanics, including kinematics, particle dynamics, work & energy, linear & angular momentum, calculus of variations, Lagrangian dynamics, central force motion.

PHYS 360 Electricity and Magnetism I (Units: 3)
Prerequisites: MATH 245 or MATH 376; PHYS 385; with grades of C- or better.

Intermediate course in electricity & magnetism, including electrostatics, electric fields in matter, magnetostatics, magnetic fields in matter.

PHYS 370 Thermodynamics and Statistical Mechanics (Units: 3)
Prerequisite: PHYS 320 with a grade of C- or better.

Classical thermodynamics, kinetic theory, and elementary statistical mechanics. Applications may include quantum statistics, black-body radiation, paramagnetic spin systems, and low-temperature phenomena.

PHYS 385 Introduction to Theoretical Physics I (Units: 3)
Prerequisites: PHYS 230, PHYS 240, and MATH 228 with grades of C or better; and MATH 245 or MATH 376 with a grade of C or better (may be taken concurrently).

Principles of applied mathematics and theoretical physics, including vectors & vector spaces; matrices, rotations & tensors; Fourier series & Fourier transforms; vector calculus. Applications to classical mechanics, electricity & magnetism, optics, fluid dynamics, heat transfer, relativity, quantum mechanics.

PHYS 430 Quantum Mechanics I (Units: 3)
Prerequisites: PHYS 320 and PHYS 360 with grades of C- or better.

Introductory course on quantum theory, including wave-particle duality, Schrödinger equation, Heisenberg Uncertainty Principle, Hilbert spaces & Hermitian operators, one-dimensional potentials, angular momentum, and the hydrogen atom.

PHYS 431 Quantum Mechanics II (Units: 3)
Prerequisite: PHYS 430 with a grade of C- or better.

Problems in three dimensions, matrix mechanics, spin, application to atomic and molecular physics, perturbation theory, and scattering.

PHYS 440 Computational Physics (Units: 3)
Prerequisite for PHYS 740: Graduate standing or permission of the instructor.
Prerequisites for PHYS 440: CSC 309 or MATH 209; MATH 245 or MATH 376; and PHYS 320, all with grades of C- or better; overall GPA of at least 3.0 or permission of the instructor.

Analysis and development of numerical algorithms with a focus on computer simulations of physical systems. Topics may include: finite difference methods for nonlinear ordinary differential equations and chaos theory, N-body gravitational systems and molecular dynamics; numerical linear algebra; Fast Fourier Transforms, finite difference and spectral methods for partial differential equations; Monte Carlo methods for integration, Markov chains, statistical mechanics and spin systems; introduction to parallel programming. Lecture, 2 units; laboratory, 1 unit. (PHYS 740/PHYS 440 is a paired course offering. Students who complete the course at one level may not repeat the course at the other level.)

PHYS 450 Introduction to Solid State Physics (Units: 3)
Prerequisites: PHYS 320 and PHYS 360 with grades of C- or better.

Crystal structure, x-ray diffraction, lattice vibrations, models of electrical conductivity; electron energy bands in crystals; electrons and holes in semiconductors.

PHYS 457 Introduction to Analog Electronics (Units: 4)
Prerequisites: PHYS 230 with a grade of C or better; MATH 245 or MATH 376 recommended (may be taken concurrently).

Linear network analysis techniques; phasors; diodes; bipolar junction transistors; field-effect transistors; operational amplifiers. Classwork, 3 units; laboratory, 1 unit.

PHYS 460 Electricity and Magnetism II (Units: 3)
Prerequisite: PHYS 360 with a grade of C- or better.

Intermediate course in electricity and magnetism, including electrodynamics, conservation laws, electromagnetic waves, potentials and fields, radiation, electrodynamics and relativity.

PHYS 480 Introduction to Optics & Photonics (Units: 3)
Prerequisites: PHYS 320 and PHYS 360 with grades of C- or better.

An introduction to optics, including geometric optics and optical instrumentation, wave equations and superposition of waves, properties of lasers, interference of light and optical interferometry, coherence, fiber optics, Fraunhofer diffraction, diffraction gratings, Fresnel diffraction, polarization, Fourier optics, holography, and photonics.

PHYS 491GW Advanced Laboratory Techniques I - GWAR (Units: 3)
Prerequisites: GE Areas A1, A2, and A3; PHYS 320 and PHYS 321 with grades of C- minus or better; CSC 309 strongly recommended.

Advanced laboratory techniques for experimental physics, including measurement & data analysis techniques and computer-based methods for data acquisition & analysis. Experiments include atomic, molecular, and optical physics, solid-state physics, and nuclear physics. Emphasizes learning and practicing the standards and format for writing scientific reports and papers. Seminar, 2 units; Laboratory, 1 unit. (ABC/NC grading only)
Course Attributes:

- Graduation Writing Assessment

PHYS 685 Instructional Methods in Teaching Physics (Unit: 1)
Prerequisite: Upper-division standing.

Pedagogical strategies and principles of teaching and learning in STEM. Seminar for students in their first Learning Assistant (LA) or Supplemental Instruction (SI) position.

PHYS 686 Experiences in Teaching Physics (Unit: 1)
Prerequisite: Upper-division standing.

Activity practicum for students serving as Learning Assistants (LAs) in STEM courses. LAs will directly assist STEM instructors in facilitating active learning in their classrooms. May be repeated for a total of 6 units.

PHYS 695 Culminating Experience in Physics (Unit: 1)
Prerequisite: Final semester of a Physics degree program.

Preparation of a portfolio of work completed in classes required for the degree. The final examination will be the ETS physics major field test.

PHYS 697 Senior Project (Units: 1-3)
Prerequisite: PHYS 491; permission of the faculty adviser.

Participation in experimental or theoretical project under the direction of faculty member. Written report of specific observations and calculations required. May be repeated with permission of the advisor.

PHYS 699 Independent Study (Units: 1-3)
Prerequisite: Approval of department and permission of the instructor.

Study in the laboratory or library under the direction of a member of the department. For students majoring or minoring in physics. Student must present a detailed written report of the work accomplished to the department. May be repeated for a total of 12 units.

PHYS 701 Classical Mechanics (Units: 3)
Prerequisite: Graduate standing or permission of the instructor.

Lagrangian and Hamiltonian mechanics; motion in arbitrary central force potentials; canonical transformation theory; Liouville's theorem; computer visualizations of phase space trajectories and topologies; collisionless Boltzmann equation applied to stellar dynamics; Jeans theorems, orbital anisotropy, and phase space distribution functions.

PHYS 704 Electrodynamics (Units: 3)
Prerequisites: Graduate standing or permission of the instructor. PHYS 785 strongly recommended.

Boundary-value problems in electrostatics; multipoles, electrostatics of macroscopic media, dielectrics; magnetostatics, Faraday's Law, quasi-static fields; Maxwell equations, macroscopic electromagnetism, conservation laws; plane electromagnetic waves and wave propagation.

PHYS 706 Quantum Mechanics (Units: 3)
Prerequisites: Graduate standing or permission of the instructor. PHYS 785 strongly recommended.

Bound states, collision theory, matrix mechanics, symmetry and groups, perturbation theory.

PHYS 710 Advanced Laboratory Techniques II (Units: 3)
Prerequisite: Graduate standing or permission of the instructor.

Techniques of electronic instrumentation, computerized data acquisition, digital signal processing, and data analysis designed to prepare the student for experimental research work in academic and industrial laboratories. Classwork, 2 units; laboratory, 1 unit.

PHYS 712 Physics of Plasmas (Units: 3)
Prerequisites: Graduate standing or permission of the instructor.

Fundamental properties of plasmas. Motion of charged particles in electromagnetic fields. Kinetic theory of plasmas, including the Boltzmann and Vlasov equations. Fluid theory of plasmas, including magnetohydrodynamics. Waves and instabilities. Applications to controlled thermonuclear fusion and space physics.

PHYS 715 Lasers and Quantum Optics (Units: 3)
Prerequisite: Graduate standing or permission of the instructor.

Atom-field interaction, stimulated emission, dipole oscillations, the ammonia maser, semi-classical laser theory, coherent states, quantum laser theory, Fourier optics, and holographic interferometry.

PHYS 725 Special and General Relativity (Units: 3)
Prerequisite: Graduate standing or permission of the instructor.

Tensor formulation of special relativity with astrophysical applications. Riemannian geometry. The Einstein field equations applied to Mercury's orbit, black holes, gravitational lensing, cosmology, and interstellar travel. Computer visualizations of spacetimes and orbits.

PHYS 726 Quantum Field Theory (Units: 3)
Prerequisites: PHYS 706 or permission of the instructor.

Relativistic wave equations; quantization of the scalar, Dirac, and Maxwell fields. The LSZ reduction formula for S-matrix elements. Path-Integral evaluation of time-ordered products. Tree-level Feynman diagrams in quantum electrodynamics, and an introduction to non-abelian gauge theory.

PHYS 730 Photonics and Nano Materials (Units: 3)
Prerequisites: Graduate standing or permission of the instructor.

Introduction to light-matter interactions in nanostructures, including basic properties of electromagnetic waves and quantum particles, wave optics and wave mechanics, electrons in periodic structures and quantum confinement effects, semiconductor nanocrystals (quantum dots), nanoplasmonics, multilayer structures, metamaterials, photonic crystals, photonic circuitry. Applications to microscopy, optical antennas, devices for opto-mechanics, energy conversion, biomedicine, nanophotonics for communication and quantum information science.

PHYS 740 Computational Physics (Units: 3)
Prerequisite for PHYS 740: Graduate standing or permission of the instructor.
Prerequisites for PHYS 440: CSC 309 or MATH 209; MATH 245 or MATH 376; and PHYS 320, all with grades of C- or better; overall GPA of at least 3.0 or permission of the instructor.

Analysis and development of numerical algorithms with a focus on computer simulations of physical systems. Topics may include: finite difference methods for nonlinear ordinary differential equations and chaos theory, N-body gravitational systems and molecular dynamics; numerical linear algebra; Fast Fourier Transforms, finite difference and spectral methods for partial differential equations; Monte Carlo methods for integration, Markov chains, statistical mechanics and spin systems; introduction to parallel programming. Lecture, 2 units; laboratory, 1 unit. (PHYS 740/PHYS 440 is a paired course offering. Students who complete the course at one level may not repeat the course at the other level.)

PHYS 775 Statistical Mechanics (Units: 3)
Prerequisite: Graduate standing or permission of the instructor.

Fundamental methods of statistical mechanics: probability, phase space, distribution functions, partition functions. Maxwell-Boltzmann, Fermi-Dirac, and Bose-Einstein statistics. Phase transitions, Monte Carlo method, transport theory.

PHYS 785 Theoretical Physics (Units: 3)
Prerequisite: Graduate standing or permission of the instructor.

Advanced concepts and techniques in mathematics applied to problems in physics. Applications in mechanics, electricity and magnetism, and fluids.

PHYS 885 Inclusive Pedagogy for the Physical Sciences (Units: 3)
Prerequisite: Graduate standing or permission of the instructor.

Development and refinement of effective, evidence-based, student-centered teaching strategies for the physical sciences with a special focus on inclusive practices to foster equity. Activities include discussion, reflection, peer observations, and projects.

PHYS 890 Introduction to Physics Research (Units: 1-3)
Prerequisite: Graduate standing.

Introduction to methods of physics research. May be repeated for a total of 5 units. (CR/NC only)

PHYS 891 Physics Research Design (Units: 1-3)
Prerequisites: Passed Level 1 Written English Proficiency Requirement and have research project approved.

Elements of Physics/Astronomy research proposals: literature review, project significance, and feasibility, materials and methods, budget, data analysis and presentation, statistical significance, reference notation. May be repeated for a total of 4 units.

PHYS 895 Culminating Project (Units: 3)
Prerequisites: Advancement to Candidacy (ATC) and Proposal for Culminating Experience (PCE) forms must be approved by the Division of Graduate Studies before registration.

Independent and original culminating project in physics under faculty supervision leading to written project report and oral defense of the project. Culminating projects could include: development of new teaching/curricular modules, portfolios of science writing/journalism, internships in science museums/planetaria or industrial or national research labs, development of technical reports/manuals for new scientific instruments, etc. (CR/NC, RP)

PHYS 896 Directed Reading in Physics (Units: 1-3)
Prerequisite: Graduate standing.

Readings/tutorials to achieve better understanding of specific topics based on individual student need. Focus on review and integration of core concepts in preparation for the comprehensive oral examination. (Does not count toward MS degree requirements.) (CR/NC only)

PHYS 896EXM Culminating Experience Examination (Unit: 0)
Prerequisites: Advancement to Candidacy (ATC) and Proposal for Culminating Experience (PCE) forms must be approved by the Division of Graduate Studies before registration.

Comprehensive oral examination on core topics in physics. (CR/NC, RP)

PHYS 897 Research (Units: 1-3)
Prerequisite: Completed undergraduate major in physics.

Independent and original laboratory investigation under supervision of a staff member. May be repeated. (Plus-minus letter grade, CR/NC, RP)

PHYS 898 Master's Thesis (Units: 3)
Prerequisites: Permission of the instructor and approval of Advancement to Candidacy (ATC) and Culminating Experience (CE) forms by Graduate Studies.

Advancement to Candidacy and Proposal for Culminating Experience Requirement forms must be approved by the Graduate Division before registration. (CR/NC, RP grading only)

PHYS 899 Independent Study (Units: 1-3)
Prerequisite: Approval of department and permission of the instructor.

Study in the laboratory or library under the direction of a member of the department. For graduate students in physics. The student must present a detailed written report of the work accomplished to the department. May be repeated.