PHYSICS AND ASTRONOMY

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The Department of Physics and Astronomy at the University of Denver combines a tradition of individualized instruction with a contemporary research focus. The department underwent a strong expansion with nine tenure-track and two teaching professor positions filled since 2006. Our diverse and dynamic faculty of 12 includes four women and come from seven different countries. We provide an attentive, hands-on research and learning community for undergraduate and graduate students up to the Ph.D. level. The department also offers a low student-to-faculty ratio in all advanced and graduate physics and astronomy courses and stresses individualized attention to each student. The program is recognized by the APS among US PhD-granting departments for our high percentage (50%) of female graduates: placing second nationally at the undergraduate level and third at the graduate level (APS data for the period 2011-2013).

The department has major research thrusts in stellar astronomy/astrophysics, biophysics, and condensed matter/materials physics. Our faculty members are internationally recognized and accomplished researchers. The department is a part of the University of Denver's interdisciplinary Molecular and Cellular Biophysics program (https://science.du.edu/biophysics/). Major state-of-the-art instrumentation is available both in the department and through collaborations with nearby national institutes in the region (NIST and NREL). Also, the University of Denver maintains our own Linux cluster for in-house high-performance computational needs.

Doctor of Philosophy in Physics

Degree and GPA Requirements

Bachelor's degree: All graduate applicants must hold an earned baccalaureate from a regionally accredited college or university or the recognized equivalent from an international institution.

University GPA requirement: The minimum grade point average for admission consideration for graduate study at the University of Denver must meet one of the following criteria:

- A cumulative 2.5 on a 4.0 scale for the baccalaureate degree.
- A cumulative 2.5 on a 4.0 scale for the last 60 semester credits or 90 quarter credits (approximately two years of work) for the baccalaureate degree.
- An earned master's degree or higher from a regionally accredited institution or the recognized equivalent from an international institution supersedes the minimum GPA requirement for the baccalaureate.
- A cumulative GPA of 3.0 on a 4.0 scale for all graduate coursework completed for applicants who have not earned a master's degree or higher.

Standardized Test Scores

- GRE scores are optional for admission to this program. Applications submitted without scores will receive full consideration. Every application undergoes a comprehensive evaluation, including a careful review of all application materials.

  If you choose to submit test scores, you may upload your Test Taker Score Report PDF, which is considered unofficial. Official scores must be received directly from the appropriate testing agency upon admission to the University of Denver. The ETS institution code to submit GRE scores to the University of Denver is 4842.

English Language Proficiency Test Score Requirements

The minimum TOEFL/IELTS/C1 Advanced/Duolingo English Test score requirements for this degree program are:

- Minimum TOEFL Score (Internet-based test): 80
- Minimum IELTS Score: 6.5
- Minimum C1 Advanced Score: 176
- Minimum Duolingo English Test Score: 115

Master of Arts in Physics

Degree and GPA Requirements

Bachelor's degree: All graduate applicants must hold an earned baccalaureate from a regionally accredited college or university or the recognized equivalent from an international institution.

University GPA requirement: The minimum grade point average for admission consideration for graduate study at the University of Denver must meet one of the following criteria:

- A cumulative 2.5 on a 4.0 scale for the baccalaureate degree.
- A cumulative 2.5 on a 4.0 scale for the last 60 semester credits or 90 quarter credits (approximately two years of work) for the baccalaureate degree.
- An earned master's degree or higher from a regionally accredited institution or the recognized equivalent from an international institution supersedes the minimum GPA requirement for the baccalaureate.
- A cumulative GPA of 3.0 on a 4.0 scale for all graduate coursework completed for applicants who have not earned a master's degree or higher.

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Master of Science in Physics

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- Minimum IELTS Score: 6.5
- Minimum C1 Advanced Score: 176
- Minimum Duolingo English Test Score: 115

Doctoral Program

Doctor of Philosophy in Physics

The Department of Physics and Astronomy offers PhD degree in physics that prepares students for careers across a spectrum of scientific pursuits. At the conclusion of your degree, you'll be equipped with the experience and knowledge necessary to build a career in the advancement of scientific knowledge or education at the highest levels, which can open doors to careers in research and development in academia, government, and private industry.

Our department offers research opportunities in theoretical, experimental and computational astronomy and astrophysics, biophysics, and condensed matter and materials physics. PhD candidates in the program will work closely with faculty advisors to create a path of study that culminates in a dissertation defense based on independent research of a publishable quality.

Degree Requirements

Coursework Requirements

Both 4000- and 3000-graduate level courses may be applied toward the degree, with the approval of the Graduate Committee or the Dissertation Committee.

Code	Title	Credits
Graduate Core Courses		**19-23**
Physics & Astronomy Graduate Core Courses are the following 8 courses (19-23 qtr hrs) that all students are expected to take during the first two years in the program:		
PHYS 4611	Adv Electricity & Magnetism I	3
PHYS 4612	Adv Electricity & Magnetism II	3
PHYS 4111	Quantum Mechanics I	3
PHYS 4112	Quantum Mechanics II	3
PHYS 4811	Statistical Mechanics I	4
PHYS 4001	Introduction to Research I	1,2
PHYS 4002	Introduction to Research II	1-3
PHYS 4003	Introduction to Research III	1,2
Additional Coursework		**71-67**
Minimum credits required for the degree		**90**

Minimum credits required for degree: 90 of which a minimum of 60 must be in Physics and Astronomy including the Graduate Core Courses, which constitute 19-23 quarter hours.

Non-Course Requirements

- Regular attendance at the Physics and Astronomy colloquia;
- Annual presentation at the Physics and Astronomy colloquia;
- Passing Comprehensive Examination at the PhD level;
- Advancement to Preliminary Candidacy at the PhD level;
- Formation of the Dissertation Committee;
- Passing Oral Dissertation Research Proposal;
- Advancement to Candidacy at the PhD level;
- Dissertation;
- Dissertation Defense. Three departmental faculty members and an Outside Chair are required for the Oral Defense.

Other Degree Requirements

- Good academic standing: a GPA of 3.0 or higher;
- No grades lower than C- are accepted toward the degree;

Master's Programs

Master of Arts in Physics

The Department of Physics and Astronomy offers a Master of Arts (MA) in Physics that prepares the student for a wide variety of jobs. The MA degree is intended primarily for students who are seeking an advanced degree without a significant research component. For instance, the MA degree is appropriate for students pursuing careers in pre-college or community college teaching, planetarium or museums, or as technical representatives of various organizations. With complementary courses in education, MA graduates are well qualified to teach at the secondary level. The main difference between the MA and MS degree is that a research thesis is not required for the MA degree. However, students pursuing the MA degree will get exposed to some research experience through Introduction to Research courses in their first year in the program.

Degree Requirements

Coursework Requirements

Both 4000- and 3000-graduate level courses may be applied toward the degree, with the approval of the Graduate Committee or the Master's Committee.

Code	Title	Credits
Graduate Core Courses		**19-23**
Physics & Astronomy Graduate Core Courses are the following 8 courses (19-23 qtr hrs) that all students are expected to take during the first two years in the program:		
PHYS 4611	Adv Electricity & Magnetism I	3
PHYS 4612	Adv Electricity & Magnetism II	3
PHYS 4111	Quantum Mechanics I	3
PHYS 4112	Quantum Mechanics II	3
PHYS 4811	Statistical Mechanics I	4
PHYS 4001	Introduction to Research I	1,2
PHYS 4002	Introduction to Research II	1-3
PHYS 4003	Introduction to Research III	1,2
Additional Coursework		**26-22**
Minimum credits required for the degree		**45**

Minimum credits required for degree: 45 including the Graduate Core Courses, which constitute 19-23 quarter hours

Non-course requirements:

- Good academic standing: a GPA of 3.0 or higher;
- No grades lower than C- are accepted toward the degree;
- Regular attendance at the Physics and Astronomy colloquia.

Master of Science in Physics

The Department of Physics and Astronomy offers a Master of Science (MS) in Physics that prepares the student for a wide variety of jobs in industry, government and educational institutions. Our graduates have obtained industrial or governmental laboratory research positions, entered pre-college or community college teaching, joined planetarium or museum staffs, and become technical representatives of various organizations. With complementary courses in education, MS graduates are well qualified to teach at the secondary level. The MS in Physics is also a popular course of study and professional improvement for people already working in industry. For those currently employed, research projects can usually be matched to the employer's programs, and often someone from the industry can serve as co-advisor so that the continuing education benefits both the student and the employer.

Degree Requirements

Coursework Requirements

Both 4000- and 3000-graduate level courses may be applied toward the degree, with the approval of the Graduate Committee or the Master's Committee.

Code	Title	Credits
Graduate Core Courses		**19-23**
Physics & Astronomy Graduate Core Courses are the following 8 courses (19-23 qtr hrs) that all students are expected to take during the first two years in the program:		
PHYS 4611	Adv Electricity & Magnetism I	3
PHYS 4612	Adv Electricity & Magnetism II	3
PHYS 4111	Quantum Mechanics I	3
PHYS 4112	Quantum Mechanics II	3
PHYS 4811	Statistical Mechanics I	4
PHYS 4001	Introduction to Research I	1,2
PHYS 4002	Introduction to Research II	1-3
PHYS 4003	Introduction to Research III	1,2
Additional Coursework		**26-22**
Minimum credits required for the degree		**45**

Minimum credits required for degree: 45 including the Graduate Core Courses, which constitute 19-23 quarter hours

Non-Course Requirements

- Regular attendance at the Physics and Astronomy colloquia;
- Annual presentation at the Physics and Astronomy colloquia;
- Passing Comprehensive Examination at the MS level;
- Advancement to MS Candidacy;
- Formation of the Master's Committee;
- Thesis;
- Thesis Defense. Two departmental faculty members and an Outside Chair are required for the Oral Defense.

Other Degree Requirements

- Good academic standing: a GPA of 3.0 or higher;
- No grades lower than C- are accepted toward the degree;

PHYS 3111 Quantum Physics I (4 Credits)
First of a two-quarter sequence. The Schrödinger equation: interpretation of wave functions; the uncertainty principle; stationary states; the free particle and wave packets; the harmonic oscillator; square well potentials. Hilbert space: observables, commutator algebra, eigenfunctions of a Hermitian operator; the hydrogen atom and hydrogenic atoms. Prerequisites: PHYS 2252, PHYS 2260, PHYS 2556, PHYS 3612 and MATH 2070.

PHYS 3112 Quantum Physics II (4 Credits)
Second of a two-quarter sequence. Angular momentum and spin; identical particles; the Pauli exclusion principle; atoms and solids: band theory; perturbation theory; the fine structure of hydrogen; the Zeeman effect; hyperfine splitting; the variational principle; the WKB approximation; tunneling; time dependent perturbation theory; emission and absorption of radiation. Scattering: partial wave analysis; the Born approximation. Prerequisite: PHYS 3111.

PHYS 3251 Astrophysics: Radiative Processes (4 Credits)
Because light is the primary means by which astronomers learn about the Universe, understanding the production and subsequent behavior of light is key to interpreting astronomical observations. This course introduces students to the physics of astrophysical radiation and its interaction with matter as it travels from its source to our detectors. Topics may include radiative transfer, emission and absorption processes, Compton processes, synchrotron radiation, thermodynamic equilibrium, radiative and collisional excitation, and spectroscopy of atoms and molecules. The course is aimed at advanced undergraduates, as well as graduate students focusing on astrophysics research. Credit can apply toward physics or astrophysics minor. Prerequisites: PHYS 2252 and MATH 1953, or instructor's permission.

PHYS 3252 Astrophysics: Observations (4 Credits)
Astronomy is fundamentally an observational science and as such it is important for practitioners to understand how their data are collected and analyzed. This course is therefore a comprehensive review of current observational techniques and instruments, aimed at advanced undergraduates, as well as graduate students focusing on astrophysics research. This class introduces students to the capabilities and limitations of different types of instruments while exploring the sources and types of noise and providing statistical tools necessary for interpreting observational data. Credit can apply toward physics or astrophysics minor. Prerequisites: PHYS 2252 and MATH 1953, or instructor's permission.

PHYS 3254 Astrophysics: Stars (4 Credits)
Stars are the fundamental building blocks of the Universe. Hence, understanding the nature of stars is the first step toward understanding the Universe. This course is therefore intended to introduce students to the rigorous physical and mathematical treatise of stellar structure and evolution. Topics may include the theoretical origins and applications fundamental equations of stellar structure and other supporting equations, and theoretical and observational applications of stellar evolution. The course is aimed at advanced undergraduates, as well as graduate students focusing on astrophysics research. Credit can apply toward Physics major or Astrophysics minor. Prerequisites: PHYS 2252 and MATH 1953, or instructor's permission.

PHYS 3270 Workshop: Practical Astronomy (1-5 Credits)
Capstone coursework featuring studies in experimental, computational, and/or theoretical work in astronomy and astrophysics. Credit can apply toward physics or astrophysics minor.

PHYS 3510 Analytical Mechanics I (4 Credits)
Lagrangian and Hamiltonian mechanics. Prerequisites: PHYS 1113, PHYS 1213, or PHYS 1214 and MATH 2070 and consent of instructor.

PHYS 3611 Electromagnetism I (4 Credits)
First of a two-quarter sequence. Vector algebra; differential vector calculus (gradient, divergence and curl); integral vector calculus (gradient, divergence and Stokes' Theorems); line, surface and volume integrals; Electrostatics: the electric field, electric potential, work and energy in electrostatics; method of images, boundary value problems and solutions to Laplace's equation in Cartesian, spherical and cylindrical coordinates; multipole expansion of the electric potential; electric fields in matter: polarization; the electric displacement vector; boundary conditions, linear dielectrics. Magnetostatics: magnetic fields and forces. Prerequisites: PHYS 1113, PHYS 1213, or PHYS 1214 and MATH 2070.

PHYS 3612 Electromagnetism II (4 Credits)
Second of a two-quarter sequence. Magnetic vector potential; magnetic fields in matter: magnetization; fields of magnetized objects; linear and nonlinear magnetic materials; electromotive force, Ohm's law; electromagnetic induction; Faraday's law; Maxwell's equations; the displacement current; boundary conditions; the Poynting theorem; momentum and energy density of the fields; the Maxwell stress tensor; the wave equation and electromagnetic waves in vacuum and matter; absorption and dispersion; wave guides; the potential formulation and gauge transformations; retarded potentials; dipole radiation. Prerequisite: PHYS 3611.

PHYS 3700 Advanced Topics: General (3 Credits)
Offered irregularly, depending on demand. May be taken more than once for credit. Prerequisite: instructor's permission.

PHYS 3711 Optics I (4 Credits)
First of a two-quarter sequence. Gaussian optics and ray tracing; matrix methods and application to optical design; elementary theory of aberrations; light as electromagnetic wave, diffraction and interference; interferometers and their applications. Elementary theory of coherence; selected topics. May include laboratory work as appropriate. Prerequisites: PHYS 1113, PHYS 1213 or PHYS 1214, and MATH 2070.

PHYS 3841 Thermal Physics I (4 Credits)
First of a two-quarter sequence. Laws of thermodynamics; thermal properties of gases and condensed matter; kinetic theory of gases, classical and quantum statistics. Prerequisites: PHYS 1113, PHYS 1213 or PHYS 1214 and MATH 2070.

PHYS 3991 Independent Study (1-10 Credits)

PHYS 3995 Independent Research (1-10 Credits)

PHYS 4001 Introduction to Research I (1,2 Credit)
This course is the first of the 3-course sequence designed to provide the opportunity of learning fundamental skills to conduct independent research in any physical science discipline. In this course, students review essential material in mathematical physics, learn basic programming techniques and improve upon their skills in literature search and scientific writing, especially proposal writing. Special in-class seminars in collaboration with the Penrose Library and Writing and Research Center are scheduled. Student are introduced to research conducted by Physics and Astronomy faculty so that they can choose a faculty member with whom to take on a Winter Research Project during the winter interterm and winter quarter as part of Introduction to Research II. Students must prepare and submit a research proposal before the end of the fall quarter.

PHYS 4002 Introduction to Research II (1-3 Credits)
This is the second of the 3-course sequence to provide the opportunity of learning fundamental skills to conduct independent research in any physical science discipline. In this course, students conduct an independent research or study project that they have outlined in the research proposal they submitted as part of Introduction to Research I under supervision of a faculty advisor of their choosing. At the same time, students have time to review issues that we face as researchers. Prerequisites: PHYS 4001 and consent of a faculty research advisor.

PHYS 4003 Introduction to Research III (1,2 Credit)
This is the third of the 3-course sequence to provide students with the opportunity of learning fundamental skills to conduct independent research in any physical science disciplines. In this course, students complete their Winter research project conducted as part of Introduction to Research II and present the results in writing as a term paper and in oral presentation as part of the Departmental Colloquia. Special in-class sessions in collaboration with the Writing and Research Center are included. Prerequisite: PHYS 4002.

PHYS 4100 Foundations of Biophysics (3 Credits)
Focus of the course is on application of basic physics principles to the study of cells and macromolecules. Topics include diffusion, random processes, thermodynamics, reaction equilibriums and kinetics, computer modeling. Must be admitted to the MCB PhD program or related graduate program with instructor approval. Cross listed with BIOP 4100.

PHYS 4111 Quantum Mechanics I (3 Credits)

PHYS 4112 Quantum Mechanics II (3 Credits)

PHYS 4251 Intro to Astrophysics I (3 Credits)

PHYS 4252 Intro to Astrophysics II (3 Credits)

PHYS 4255 Astrophysics: Black Holes, Cosmology, and Relation to Other Systems (4 Credits)
The very small, the very large, and the very gravitational provide extreme tests of physics. In this course, we will cover two of these: cosmology, i.e., the universe on large scales, or as a whole (the very large) and black holes (the very gravitational). We will cover some basics of special and general relativity and quantum mechanics relevant to these topics, and discuss recent research testing these frontiers of physics, emphasizing analogies that help to relate these exotica to more familiar physical systems.

PHYS 4310 Quantum Electronics & Topology (4 Credits)
This Physics course will introduce students to the basics of electrical and topological phenomena in quantum materials. The course will focus on phenomenology in two-dimensional (2D) materials, in which quantum electronic transport and topology play a major role. Starting from quantum mechanics and condensed matter basics, we will introduce the most widely used 2D systems, such as graphene, and explore their electronic properties. Students will learn about modern concepts in the field of 2D materials, such as topology, electronic correlations, moiré physics, and fractionalization. Students will also have hands-on experience with basic electrical measurements and 2D device fabrication, designed to supplement the lecture.

PHYS 4320 Introduction to Quantum Materials (4 Credits)
This physics course will introduce students to the recent experimental and theoretical developments in the field of quantum materials. Students will gain a basic understanding of how reducing the dimensions of materials to the nanoscale can produce extraordinary physical properties. The course will focus on fundamentals and recent advances in the fields of quantum transport, 2D materials, strongly correlated electronic systems, topological materials, and superconductivity. The goal of this course is to prepare students to engage with the modern condensed matter physics research and application engineering of novel quantum materials. Prerequisites: PHYS 4411 Advanced Condensed Matter or instructor's permission.

PHYS 4333 Magnetism and Spintronics: from Classical to Quantum (4 Credits)
This Physics course will introduce students the fundamentals of magnetism and spintronics as well as their applications in both classical world and quantum world. Besides understanding the principle of modern technologies such as motors, hard disk drives, MRI etc., the students will also have hands-on experience with microelectronics, microwave and laser techniques specially designed to supplement the lecture.

PHYS 4350 Physics and information (4 Credits)
Students in Physical Sciences are often well versed in the art of model building but less so in the process of model-selection when multiple models can describe the same data. Students rarely learn tools beyond curve fitting and least square error minimization for model selection. Consequently, students are often unaware of the scope of different tools and fail to make judicious choice of algorithms/theories when faced with diverse problems. For example, building a model from data is very different from generating data (stochastic or deterministic) from a model. Next consider two contrasting challenges of model building i) when there is limited data vs ii) when there is too much data. For the first problem -- inferring models from limited data -- the solution can be traced back to Boltzmann's formulation of Statistical Physics describing motion of atoms. The connection between Information theory, Inference and Boltzmann's description, however, is often overlooked in introductory or even advanced classes in Physics, and Statistics. Studying these similarities can unlock novel solutions for problems well outside of thermodynamics, even as far as Image processing, Biology and Network science. Inference also requires us to appreciate fundamental topics in Probability -- difference between frequentist and non-frequentist approach, Bayesian formalism -- that are rarely taught to physical scientists, life scientists or engineers. At the other extreme, faced with data deluge, we routinely ask: how do we make sense of too much data ? We use clustering, PCA, Neural Networks. In this course we will discuss and connect all these seemingly disparate concepts and apply them -- at the appropriate context -- to diverse problems in Physics, Chemistry, Biology and beyond. In the process we will gain an in-depth knowledge about commonly heard but perhaps less understood topics such as: Entropy, Likelihood maximization, Bayesian statistics, PCA, Classification algorithms, and Neural Networks. We will also address another often overlooked but fundamental and fascinating topic, biology's inherent ability to encode and decode information. Currently there is no such course that address all these topics in Information and Data Science in an unified manner -- deeply connecting their formal basis, regime of applicability -- grounded on physical principles, with a forward looking approach towards application in many areas well outside of traditional sciences. A lot of learning in the course will happen `on the fly', where the tools and application problems are learnt as needed.

PHYS 4411 Advanced Condensed Matter I (3 Credits)
Materials structure; structure analysis; elastic properties; defects; plastic mechanical properties; thermal properties and phonons; free electron gas; energy bands and Fermi surfaces; crystalline and amorphous semiconductors; quasiparticles and excitations; electrical properties and ferroelectrics; magnetic properties and ferromagnetics; classical and high-Tc superconductors; other advanced materials. Co-requisite: PHYS 4111.

PHYS 4412 Advanced Condensed Matter II (3 Credits)
Materials structure; structure analysis; elastic properties; defects; plastic mechanical properties; thermal properties and phonons; free electron gas; energy bands and Fermi surfaces; crystalline and amorphous semiconductors; quasiparticles and excitations; electrical properties and ferroelectrics; magnetic properties and ferromagnetics; classical and high-Tc superconductors; other advanced materials. Co-requisite: PHYS 4112.

PHYS 4511 Advanced Dynamics I (4 Credits)

PHYS 4611 Adv Electricity & Magnetism I (3 Credits)

PHYS 4612 Adv Electricity & Magnetism II (3 Credits)

PHYS 4720 Light-Matter Interaction (4 Credits)
This course will introduce the theory and applications of light-matter interactions. Fundamental theory will be explored from both semi-classical and quantum perspectives, and photon-carrier interactions will be studied in a variety of physical systems, including atoms, glasses, semiconductors, and metals. Experimental techniques will also be discussed, such as absorption, photoluminescence, and coherent spectroscopies, in addition to ultrafast nonlinear optical interactions. Students will also build their own demonstration and teaching module for elementary-age children, and will use their module to teach children at a local school.

PHYS 4750 Seminar in Physics (1 Credit)

PHYS 4811 Statistical Mechanics I (4 Credits)
Fundamentals of thermodynamics, microcanonical and canonical ensemble, quantum formulation noninteracting particle systems.

PHYS 4860 Numerical and Computational Methods in Physics (4 Credits)
The main goal of this course is to gain a better understanding of physical problems by solving them numerically; in the process, students learn about several numerical methods and computational techniques that have a very broad range of applications in many other scientific fields. Depending on the problem, students work with a software package (Mathematica), and also acquire coding experience in different programming languages. Graduate students carry out projects involving more complex simulation and numerical methods currently used in many areas of condensed matter physics, quantum chemistry and biophysics, such as Density Functional calculations, Monte Carlo and Molecular Dynamics methods.

PHYS 4870 Special and General Relativity (4 Credits)
This course will start with the techniques in Special Relativity and build familiarity with tensors. In the second part of the quarter, we will generalize to curved spaces and the Schwarzschild solution. And, finally, we will set up and solve the Einstein equations using the Cartan equations of structure to study the Robertson Walker metric spacetime used to construct the energy budget of the universe.

PHYS 4910 Special Topics Physics (1-5 Credits)

PHYS 4991 Independent Study (1-10 Credits)

PHYS 4995 Independent Research (1-10 Credits)

Courses

PHYS 3111 Quantum Physics I (4 Credits)
First of a two-quarter sequence. The Schrödinger equation: interpretation of wave functions; the uncertainty principle; stationary states; the free particle and wave packets; the harmonic oscillator; square well potentials. Hilbert space: observables, commutator algebra, eigenfunctions of a Hermitian operator; the hydrogen atom and hydrogenic atoms. Prerequisites: PHYS 2252, PHYS 2260, PHYS 2556, PHYS 3612 and MATH 2070.

PHYS 3112 Quantum Physics II (4 Credits)
Second of a two-quarter sequence. Angular momentum and spin; identical particles; the Pauli exclusion principle; atoms and solids: band theory; perturbation theory; the fine structure of hydrogen; the Zeeman effect; hyperfine splitting; the variational principle; the WKB approximation; tunneling; time dependent perturbation theory; emission and absorption of radiation. Scattering: partial wave analysis; the Born approximation. Prerequisite: PHYS 3111.

PHYS 3251 Astrophysics: Radiative Processes (4 Credits)
Because light is the primary means by which astronomers learn about the Universe, understanding the production and subsequent behavior of light is key to interpreting astronomical observations. This course introduces students to the physics of astrophysical radiation and its interaction with matter as it travels from its source to our detectors. Topics may include radiative transfer, emission and absorption processes, Compton processes, synchrotron radiation, thermodynamic equilibrium, radiative and collisional excitation, and spectroscopy of atoms and molecules. The course is aimed at advanced undergraduates, as well as graduate students focusing on astrophysics research. Credit can apply toward physics or astrophysics minor. Prerequisites: PHYS 2252 and MATH 1953, or instructor's permission.

PHYS 3252 Astrophysics: Observations (4 Credits)
Astronomy is fundamentally an observational science and as such it is important for practitioners to understand how their data are collected and analyzed. This course is therefore a comprehensive review of current observational techniques and instruments, aimed at advanced undergraduates, as well as graduate students focusing on astrophysics research. This class introduces students to the capabilities and limitations of different types of instruments while exploring the sources and types of noise and providing statistical tools necessary for interpreting observational data. Credit can apply toward physics or astrophysics minor. Prerequisites: PHYS 2252 and MATH 1953, or instructor's permission.

PHYS 3254 Astrophysics: Stars (4 Credits)
Stars are the fundamental building blocks of the Universe. Hence, understanding the nature of stars is the first step toward understanding the Universe. This course is therefore intended to introduce students to the rigorous physical and mathematical treatise of stellar structure and evolution. Topics may include the theoretical origins and applications fundamental equations of stellar structure and other supporting equations, and theoretical and observational applications of stellar evolution. The course is aimed at advanced undergraduates, as well as graduate students focusing on astrophysics research. Credit can apply toward Physics major or Astrophysics minor. Prerequisites: PHYS 2252 and MATH 1953, or instructor's permission.

PHYS 3270 Workshop: Practical Astronomy (1-5 Credits)
Capstone coursework featuring studies in experimental, computational, and/or theoretical work in astronomy and astrophysics. Credit can apply toward physics or astrophysics minor.

PHYS 3510 Analytical Mechanics I (4 Credits)
Lagrangian and Hamiltonian mechanics. Prerequisites: PHYS 1113, PHYS 1213, or PHYS 1214 and MATH 2070 and consent of instructor.

PHYS 3611 Electromagnetism I (4 Credits)
First of a two-quarter sequence. Vector algebra; differential vector calculus (gradient, divergence and curl); integral vector calculus (gradient, divergence and Stokes' Theorems); line, surface and volume integrals; Electrostatics: the electric field, electric potential, work and energy in electrostatics; method of images, boundary value problems and solutions to Laplace's equation in Cartesian, spherical and cylindrical coordinates; multipole expansion of the electric potential; electric fields in matter: polarization; the electric displacement vector; boundary conditions, linear dielectrics. Magnetostatics: magnetic fields and forces. Prerequisites: PHYS 1113, PHYS 1213, or PHYS 1214 and MATH 2070.

PHYS 3612 Electromagnetism II (4 Credits)
Second of a two-quarter sequence. Magnetic vector potential; magnetic fields in matter: magnetization; fields of magnetized objects; linear and nonlinear magnetic materials; electromotive force, Ohm's law; electromagnetic induction; Faraday's law; Maxwell's equations; the displacement current; boundary conditions; the Poynting theorem; momentum and energy density of the fields; the Maxwell stress tensor; the wave equation and electromagnetic waves in vacuum and matter; absorption and dispersion; wave guides; the potential formulation and gauge transformations; retarded potentials; dipole radiation. Prerequisite: PHYS 3611.

PHYS 3700 Advanced Topics: General (3 Credits)
Offered irregularly, depending on demand. May be taken more than once for credit. Prerequisite: instructor's permission.

PHYS 3711 Optics I (4 Credits)
First of a two-quarter sequence. Gaussian optics and ray tracing; matrix methods and application to optical design; elementary theory of aberrations; light as electromagnetic wave, diffraction and interference; interferometers and their applications. Elementary theory of coherence; selected topics. May include laboratory work as appropriate. Prerequisites: PHYS 1113, PHYS 1213 or PHYS 1214, and MATH 2070.

PHYS 3841 Thermal Physics I (4 Credits)
First of a two-quarter sequence. Laws of thermodynamics; thermal properties of gases and condensed matter; kinetic theory of gases, classical and quantum statistics. Prerequisites: PHYS 1113, PHYS 1213 or PHYS 1214 and MATH 2070.

PHYS 3991 Independent Study (1-10 Credits)

PHYS 3995 Independent Research (1-10 Credits)

PHYS 4001 Introduction to Research I (1,2 Credit)
This course is the first of the 3-course sequence designed to provide the opportunity of learning fundamental skills to conduct independent research in any physical science discipline. In this course, students review essential material in mathematical physics, learn basic programming techniques and improve upon their skills in literature search and scientific writing, especially proposal writing. Special in-class seminars in collaboration with the Penrose Library and Writing and Research Center are scheduled. Student are introduced to research conducted by Physics and Astronomy faculty so that they can choose a faculty member with whom to take on a Winter Research Project during the winter interterm and winter quarter as part of Introduction to Research II. Students must prepare and submit a research proposal before the end of the fall quarter.

PHYS 4002 Introduction to Research II (1-3 Credits)
This is the second of the 3-course sequence to provide the opportunity of learning fundamental skills to conduct independent research in any physical science discipline. In this course, students conduct an independent research or study project that they have outlined in the research proposal they submitted as part of Introduction to Research I under supervision of a faculty advisor of their choosing. At the same time, students have time to review issues that we face as researchers. Prerequisites: PHYS 4001 and consent of a faculty research advisor.

PHYS 4003 Introduction to Research III (1,2 Credit)
This is the third of the 3-course sequence to provide students with the opportunity of learning fundamental skills to conduct independent research in any physical science disciplines. In this course, students complete their Winter research project conducted as part of Introduction to Research II and present the results in writing as a term paper and in oral presentation as part of the Departmental Colloquia. Special in-class sessions in collaboration with the Writing and Research Center are included. Prerequisite: PHYS 4002.

PHYS 4100 Foundations of Biophysics (3 Credits)
Focus of the course is on application of basic physics principles to the study of cells and macromolecules. Topics include diffusion, random processes, thermodynamics, reaction equilibriums and kinetics, computer modeling. Must be admitted to the MCB PhD program or related graduate program with instructor approval. Cross listed with BIOP 4100.

PHYS 4111 Quantum Mechanics I (3 Credits)

PHYS 4112 Quantum Mechanics II (3 Credits)

PHYS 4251 Intro to Astrophysics I (3 Credits)

PHYS 4252 Intro to Astrophysics II (3 Credits)

PHYS 4255 Astrophysics: Black Holes, Cosmology, and Relation to Other Systems (4 Credits)
The very small, the very large, and the very gravitational provide extreme tests of physics. In this course, we will cover two of these: cosmology, i.e., the universe on large scales, or as a whole (the very large) and black holes (the very gravitational). We will cover some basics of special and general relativity and quantum mechanics relevant to these topics, and discuss recent research testing these frontiers of physics, emphasizing analogies that help to relate these exotica to more familiar physical systems.

PHYS 4310 Quantum Electronics & Topology (4 Credits)
This Physics course will introduce students to the basics of electrical and topological phenomena in quantum materials. The course will focus on phenomenology in two-dimensional (2D) materials, in which quantum electronic transport and topology play a major role. Starting from quantum mechanics and condensed matter basics, we will introduce the most widely used 2D systems, such as graphene, and explore their electronic properties. Students will learn about modern concepts in the field of 2D materials, such as topology, electronic correlations, moiré physics, and fractionalization. Students will also have hands-on experience with basic electrical measurements and 2D device fabrication, designed to supplement the lecture.

PHYS 4320 Introduction to Quantum Materials (4 Credits)
This physics course will introduce students to the recent experimental and theoretical developments in the field of quantum materials. Students will gain a basic understanding of how reducing the dimensions of materials to the nanoscale can produce extraordinary physical properties. The course will focus on fundamentals and recent advances in the fields of quantum transport, 2D materials, strongly correlated electronic systems, topological materials, and superconductivity. The goal of this course is to prepare students to engage with the modern condensed matter physics research and application engineering of novel quantum materials. Prerequisites: PHYS 4411 Advanced Condensed Matter or instructor's permission.

PHYS 4333 Magnetism and Spintronics: from Classical to Quantum (4 Credits)
This Physics course will introduce students the fundamentals of magnetism and spintronics as well as their applications in both classical world and quantum world. Besides understanding the principle of modern technologies such as motors, hard disk drives, MRI etc., the students will also have hands-on experience with microelectronics, microwave and laser techniques specially designed to supplement the lecture.

PHYS 4350 Physics and information (4 Credits)
Students in Physical Sciences are often well versed in the art of model building but less so in the process of model-selection when multiple models can describe the same data. Students rarely learn tools beyond curve fitting and least square error minimization for model selection. Consequently, students are often unaware of the scope of different tools and fail to make judicious choice of algorithms/theories when faced with diverse problems. For example, building a model from data is very different from generating data (stochastic or deterministic) from a model. Next consider two contrasting challenges of model building i) when there is limited data vs ii) when there is too much data. For the first problem -- inferring models from limited data -- the solution can be traced back to Boltzmann's formulation of Statistical Physics describing motion of atoms. The connection between Information theory, Inference and Boltzmann's description, however, is often overlooked in introductory or even advanced classes in Physics, and Statistics. Studying these similarities can unlock novel solutions for problems well outside of thermodynamics, even as far as Image processing, Biology and Network science. Inference also requires us to appreciate fundamental topics in Probability -- difference between frequentist and non-frequentist approach, Bayesian formalism -- that are rarely taught to physical scientists, life scientists or engineers. At the other extreme, faced with data deluge, we routinely ask: how do we make sense of too much data ? We use clustering, PCA, Neural Networks. In this course we will discuss and connect all these seemingly disparate concepts and apply them -- at the appropriate context -- to diverse problems in Physics, Chemistry, Biology and beyond. In the process we will gain an in-depth knowledge about commonly heard but perhaps less understood topics such as: Entropy, Likelihood maximization, Bayesian statistics, PCA, Classification algorithms, and Neural Networks. We will also address another often overlooked but fundamental and fascinating topic, biology's inherent ability to encode and decode information. Currently there is no such course that address all these topics in Information and Data Science in an unified manner -- deeply connecting their formal basis, regime of applicability -- grounded on physical principles, with a forward looking approach towards application in many areas well outside of traditional sciences. A lot of learning in the course will happen `on the fly', where the tools and application problems are learnt as needed.

PHYS 4411 Advanced Condensed Matter I (3 Credits)
Materials structure; structure analysis; elastic properties; defects; plastic mechanical properties; thermal properties and phonons; free electron gas; energy bands and Fermi surfaces; crystalline and amorphous semiconductors; quasiparticles and excitations; electrical properties and ferroelectrics; magnetic properties and ferromagnetics; classical and high-Tc superconductors; other advanced materials. Co-requisite: PHYS 4111.

PHYS 4412 Advanced Condensed Matter II (3 Credits)
Materials structure; structure analysis; elastic properties; defects; plastic mechanical properties; thermal properties and phonons; free electron gas; energy bands and Fermi surfaces; crystalline and amorphous semiconductors; quasiparticles and excitations; electrical properties and ferroelectrics; magnetic properties and ferromagnetics; classical and high-Tc superconductors; other advanced materials. Co-requisite: PHYS 4112.

PHYS 4511 Advanced Dynamics I (4 Credits)

PHYS 4611 Adv Electricity & Magnetism I (3 Credits)

PHYS 4612 Adv Electricity & Magnetism II (3 Credits)

PHYS 4720 Light-Matter Interaction (4 Credits)
This course will introduce the theory and applications of light-matter interactions. Fundamental theory will be explored from both semi-classical and quantum perspectives, and photon-carrier interactions will be studied in a variety of physical systems, including atoms, glasses, semiconductors, and metals. Experimental techniques will also be discussed, such as absorption, photoluminescence, and coherent spectroscopies, in addition to ultrafast nonlinear optical interactions. Students will also build their own demonstration and teaching module for elementary-age children, and will use their module to teach children at a local school.

PHYS 4750 Seminar in Physics (1 Credit)

PHYS 4811 Statistical Mechanics I (4 Credits)
Fundamentals of thermodynamics, microcanonical and canonical ensemble, quantum formulation noninteracting particle systems.

PHYS 4860 Numerical and Computational Methods in Physics (4 Credits)
The main goal of this course is to gain a better understanding of physical problems by solving them numerically; in the process, students learn about several numerical methods and computational techniques that have a very broad range of applications in many other scientific fields. Depending on the problem, students work with a software package (Mathematica), and also acquire coding experience in different programming languages. Graduate students carry out projects involving more complex simulation and numerical methods currently used in many areas of condensed matter physics, quantum chemistry and biophysics, such as Density Functional calculations, Monte Carlo and Molecular Dynamics methods.

PHYS 4870 Special and General Relativity (4 Credits)
This course will start with the techniques in Special Relativity and build familiarity with tensors. In the second part of the quarter, we will generalize to curved spaces and the Schwarzschild solution. And, finally, we will set up and solve the Einstein equations using the Cartan equations of structure to study the Robertson Walker metric spacetime used to construct the energy budget of the universe.

PHYS 4910 Special Topics Physics (1-5 Credits)

PHYS 4991 Independent Study (1-10 Credits)

PHYS 4995 Independent Research (1-10 Credits)