Physics

Physics is the discipline that deals with the most fundamental aspects of our universe, such as the properties of atoms, nuclei and elementary particles; the nature of the forces between them; and the collective behavior of atoms in solids, liquids and gases. It deals with the entire universe, from its birth to its ultimate fate. At the same time, physics provides the tools that help us to understand extremely complex everyday things, like the behavior of sand piles, the strength of materials, or processes in the brain. Physics seeks to discover and understand the mathematical rules that govern the behavior of things. Its early successes in comprehending motion, thermodynamics, electricity and magnetism provided a foundation upon which other physical sciences have grown.

For students planning a career in science and technology or intending to pursue graduate studies in physics, astronomy, earth sciences, environmental sciences, medical physics, meteorology or oceanography, a major in physics provides a solid foundation. The program is sufficiently flexible to allow students to combine a physics major with a second major in chemistry, mathematics or engineering; with pre-medical studies; or with other disciplines in the humanities and social sciences. In addition to the fundamentals of physics, the program is designed to give students a broad range of skills in laboratory techniques, critical thinking, computer use, and teamwork, which will serve them well in their chosen careers. In consultation with a faculty adviser, students may design a program of study to meet individual goals and interests. Physics majors are strongly encouraged to participate in physics research projects directed by faculty members.

**Introductory Physics:** The Physics 191–Physics 192 and Physics 191L–Physics 192L sequence is a calculus-based introduction to physics intended for adequately prepared students interested in majoring in science or engineering or undertaking pre-medical studies. Physics 191 fulfills the requirements for the Sam Fox School. The sequence uses interactive, active-learning techniques. Calculus I (Math 131) is a corequisite, although previous or concurrent enrollment in Calculus II (Math 132) is strongly recommended.

**Focused Physics:** The Physics 193–Physics 194 and Physics 193L–Physics 194L sequence is an advanced calculus-based introduction to physics for students with previous or concurrent enrollment in Calculus II (Math 132). This sequence is particularly addressed to students considering a physics- or mathematics-heavy science or engineering major. The department also offers several other courses of general interest to the nonscience student. In most cases, these courses have no prerequisites.

Website: [http://physics.wustl.edu](http://physics.wustl.edu)

---

**Faculty**

**Chair**

Mark Alford ([https://physics.wustl.edu/people/mark-g-alford/](https://physics.wustl.edu/people/mark-g-alford/))
Professor
PhD, Harvard University
Nuclear/particle physics

**Endowed Professors**

Ramanath Cowsik ([https://physics.wustl.edu/people/ramanath-cowsik/](https://physics.wustl.edu/people/ramanath-cowsik/))
James S. McDonnell Professor of Space Sciences
PhD, University of Bombay
Astrophysics and space sciences

Arthur Holly Compton Professor of Physics
PhD, Harvard University
Condensed matter and materials physics

Henric Krawczynski ([https://physics.wustl.edu/people/henric-krawczynski/](https://physics.wustl.edu/people/henric-krawczynski/))
Wayman Crow Professor of Physics
PhD, University of Hamburg
Experimental high-energy astrophysics

**Professors**

PhD, University of Chicago
Experimental high-energy astrophysics

PhD, Harvard University
Biophysics

PhD, Free University, Amsterdam
Many-body theory

Martin H. Israel ([https://physics.wustl.edu/people/martin-h-israel/](https://physics.wustl.edu/people/martin-h-israel/))
PhD, California Institute of Technology
Experimental cosmic-ray physics

PhD, Cornell University
Theoretical astrophysics
Zohar Nussinov (https://physics.wustl.edu/people/zohar-nussinov/)
PhD, University of California, Los Angeles
Theoretical condensed matter physics

Michael C. Ogilvie (https://physics.wustl.edu/people/michael-c-ogilvie/)
PhD, Brown University
Theoretical particle physics

Ralf Wessel (https://physics.wustl.edu/people/ralf-wessel/)
PhD, University of Cambridge
Biophysics

Li Yang (https://physics.wustl.edu/people/li-yang/)
PhD, Georgia Institute of Technology
Condensed matter and materials science

Joint Professor

Lee G. Sobotka (https://physics.wustl.edu/people/lee-sobotka/)
PhD, University of California, Berkeley
(Chemistry)
Experimental nuclear physics

Associate Professors

Francesc Ferrer (https://physics.wustl.edu/people/francesc-ferrer/)
PhD, Universitat Autònoma de Barcelona
Theoretical astro-particle physics & cosmology

Kater Murch (https://physics.wustl.edu/people/kater-murch/)
PhD, University of California, Berkeley
Quantum information and materials

Alexander Seidel (https://physics.wustl.edu/people/alexander-seidel/)
PhD, Massachusetts Institute of Technology
Theoretical condensed matter physics

Assistant Professors

Bhupal Dev (https://physics.wustl.edu/people/bhupal-dev/)
PhD, University of Maryland, College Park
Theoretical astro-particle physics & cosmology

Manel Errando (https://web.physics.wustl.edu/errando/)
PhD, Universitat Autonoma de Barcelona
High-energy astrophysics, black holes, active galactic nuclei

Erik Henriksen (https://physics.wustl.edu/people/erik-henriksen/)
PhD, Columbia University
Condensed matter and materials science

James Mertens (https://physics.wustl.edu/people/james-mertens/)
PhD, Case Western Reserve University
Theoretical high-energy astrophysics

Shankar Mukherji (https://physics.wustl.edu/people/shankar-mukherji/)
PhD, Massachusetts Institute of Technology/Harvard Medical School
Systems cell biology

Johanna Nagy (https://physics.wustl.edu/people/johanna-nagy/)
PhD, Case Western Reserve University
Experimental astrophysics

Ryan Ogliore (https://physics.wustl.edu/people/ryan-ogliore/)
PhD, California Institute of Technology
Cosmochemistry, planetary science

Saori Pastore (https://physics.wustl.edu/people/saori-pastore/)
PhD, Old Dominion University
Theoretical nuclear physics

Maria Piarulli (https://physics.wustl.edu/people/maria-piarulli/)
PhD, Old Dominion University
Theoretical nuclear physics

Sheng Ran (https://physics.wustl.edu/people/sheng-ran/)
PhD, Iowa State University
Condensed matter, quantum materials

Mikhail Tikhonov (https://physics.wustl.edu/people/mikhail-tikhonov/)
PhD, Princeton University
Microbiome, microbial ecology and evolution

Senior Lecturer

Mairin Hynes (https://physics.wustl.edu/people/kathryn-mairin-hynes/)
PhD, Washington University

Lecturer

Augusto Medeiros da Rosa (https://physics.wustl.edu/people/augusto-medeiros-da-rosa/)
PhD, Washington University

Research Professors

Sachiko Amari (https://physics.wustl.edu/people/sachiko-amari/)
PhD, Kobe University

Alexander Meshik (https://physics.wustl.edu/people/alex-meshik/)
PhD, Vernadsky Institute of Cosmochemistry

Michael Nowak (https://physics.wustl.edu/people/michael-nowak/)
PhD, Stanford University
Research Associate Professors

Jeffrey Gillis-Davis (https://physics.wustl.edu/people/jeffrey-gillis-davis/)
PhD, Rice University
Experimental astrophysics

Olga Pravdivtseva (https://physics.wustl.edu/people/olga-pravdivtseva/)
PhD, Vernadsky Institute, Russian Academy of Sciences

Research Assistant Professors

Nan Liu (https://physics.wustl.edu/people/nan-liu/)
PhD, University of Chicago

Brian Rauch (https://physics.wustl.edu/people/brian-rauch/)
PhD, Washington University

Professors Emeriti

Carl M. Bender (https://physics.wustl.edu/people/carl-bender/)
Wilfred R. and Ann Lee Konneker Professor of Physics
PhD, Harvard University

Claude W. Bernard (https://physics.wustl.edu/people/claude-bernard-0/)
PhD, Harvard University

Thomas Bernatowicz (https://physics.wustl.edu/people/thomas-j-bernatowicz/)
PhD, Washington University

Robert Binns (https://physics.wustl.edu/people/w-robert-binns/)
PhD, Colorado State University

John W. Clark (https://physics.wustl.edu/people/john-w-clark/)
PhD, Washington University

Mark S. Conradi (https://physics.wustl.edu/people/mark-s-conradi/)
PhD, Washington University

Peter A. Fedders (https://physics.wustl.edu/people/peter-fedders/)
PhD, Harvard University

Patrick C. Gibbons (https://physics.wustl.edu/people/patrick-c-gibbons/)
PhD, Harvard University

Charles M. Hohenberg (https://physics.wustl.edu/people/charles-m-hohenberg/)
PhD, University of California, Berkeley

Kazimierz Luszczynski (https://physics.wustl.edu/people/kazimierz-luszczynski/)
PhD, University of London

James G. Miller (https://physics.wustl.edu/people/james-g-miller/)
Albert Gordon Hill Professor of Physics
PhD, Washington University

Peter R. Phillips (https://physics.wustl.edu/people/peter-r-phillips/)
PhD, Stanford University

James S. Schilling (https://physics.wustl.edu/people/james-s-schilling/)
PhD, University of Wisconsin-Madison

Stuart A. Solin (https://physics.wustl.edu/people/stuart-solin-0/)
Charles M. Hohenberg Professor of Experimental Physics
PhD, Purdue University

Wai-Mo Suen (https://physics.wustl.edu/people/wai-mo-suen-0/)
PhD, California Institute of Technology

Clifford Will (https://physics.wustl.edu/people/clifford-will/)
PhD, California Institute of Technology

Majors

The Major in Physics

Required introductory courses: Majors in physics are required to complete a series of introductory courses.

They may take either:

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physics 191</td>
<td>Physics I</td>
<td>3</td>
</tr>
<tr>
<td>Physics 191L</td>
<td>Physics I Laboratory</td>
<td>1</td>
</tr>
<tr>
<td>Physics 192</td>
<td>Physics II</td>
<td>3</td>
</tr>
<tr>
<td>Physics 192L</td>
<td>Physics II Laboratory</td>
<td>1</td>
</tr>
</tbody>
</table>

or (recommended for majors):

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physics 193</td>
<td>Focused Physics I</td>
<td>4</td>
</tr>
<tr>
<td>Physics 193L</td>
<td>Focused Physics I Laboratory</td>
<td>1</td>
</tr>
<tr>
<td>Physics 194</td>
<td>Focused Physics II</td>
<td></td>
</tr>
<tr>
<td>Physics 194L</td>
<td>Focused Physics Laboratory</td>
<td></td>
</tr>
</tbody>
</table>

Required courses: In addition, majors in physics are required to complete the following courses:

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physics 322</td>
<td>Physical Measurement Laboratory</td>
<td>3</td>
</tr>
<tr>
<td>Physics 411</td>
<td>Mechanics</td>
<td>3</td>
</tr>
<tr>
<td>Physics 421</td>
<td>Electricity and Magnetism</td>
<td>3</td>
</tr>
</tbody>
</table>

One quantum physics course, chosen from the following:
**Physics (12/03/21)**

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physics 217</td>
<td>Introduction to Quantum Physics *</td>
<td>3</td>
</tr>
<tr>
<td>Physics 318</td>
<td>Introduction to Quantum Physics II</td>
<td>3</td>
</tr>
<tr>
<td>Physics 471</td>
<td>Quantum Mechanics</td>
<td>3</td>
</tr>
</tbody>
</table>

* Physics 217 does not fulfill the requirement of an upper-level course.

**One additional upper-level laboratory course**, chosen from the following:

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physics 316</td>
<td>Optics and Wave Physics Laboratory</td>
<td>3</td>
</tr>
<tr>
<td>Physics 321</td>
<td>Electronics Laboratory</td>
<td>3</td>
</tr>
<tr>
<td>Physics 360</td>
<td>Biophysics Laboratory</td>
<td>3</td>
</tr>
<tr>
<td>Physics 435</td>
<td>Nuclear and Radiochemistry Lab</td>
<td>3</td>
</tr>
</tbody>
</table>

**Upper-level courses**: Majors are required to complete a minimum of 21 units of advanced courses (300 level or higher) in Physics, excluding Physics 341, Physics 342, Physics 441, Physics 442, Physics 499 and Physics 500. These 21 units may include courses listed above. Students must receive letter grades for these advanced courses, and the course must be completed with a grade of at least a C-.

**Math courses required for the physics major**:

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Math 131</td>
<td>Calculus I</td>
<td>3</td>
</tr>
<tr>
<td>Math 132</td>
<td>Calculus II</td>
<td>3</td>
</tr>
<tr>
<td>Math 233</td>
<td>Calculus III</td>
<td>3</td>
</tr>
<tr>
<td>Math 217</td>
<td>Differential Equations</td>
<td>3</td>
</tr>
</tbody>
</table>

Students who have completed Math 203 Honors Mathematics I and Math 204 Honors Mathematics II will have fulfilled the requirement for Math 131 Calculus I, Math 132 Calculus II, and Math 233 Calculus III.

**Math courses recommended for the physics major**:

- Math 308 Mathematics for the Physical Sciences or ESE 318 Engineering Mathematics A (We recommend that this course precede Physics 421.)
- Math 309 Matrix Algebra (We recommend that this course precede Physics 471.)
- Physics 501/Math 501 and Physics 502/Math 502 also are recommended.

**Science-breadth requirement**: Majors must select three of the following courses to satisfy the science-breadth requirement.


---

**Biophysics Track**

Physics majors may concentrate in the subfield of biophysics by taking the following (as part of their distribution requirement):

**Physics requirement**:

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physics 463</td>
<td>Statistical Mechanics and Thermodynamics</td>
<td>3</td>
</tr>
</tbody>
</table>

One of the following:

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physics 450</td>
<td>Physics of the Brain</td>
<td>3</td>
</tr>
<tr>
<td>Physics 455</td>
<td>Physics of Vision</td>
<td>3</td>
</tr>
</tbody>
</table>

One of the following:

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physics 454</td>
<td>Physics of Living Systems</td>
<td>3</td>
</tr>
<tr>
<td>Physics 481</td>
<td>Critical Analysis of Scientific Data</td>
<td>3</td>
</tr>
<tr>
<td>Physics 509</td>
<td>Nonlinear Dynamics</td>
<td>3</td>
</tr>
<tr>
<td>Physics 563</td>
<td>Topics in Theoretical Biophysics</td>
<td>3</td>
</tr>
</tbody>
</table>

**Biology requirements**:

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biol 2960</td>
<td>Principles of Biology I</td>
<td>4</td>
</tr>
<tr>
<td>Biol 2970</td>
<td>Principles of Biology II</td>
<td>4</td>
</tr>
</tbody>
</table>
Note: Students wanting to have the biophysics track displayed on their transcript must send an email to the director of undergraduate studies (dus@physics.wustl.edu) at least one semester before their graduation date.

The Major in Astrophysics

Required introductory courses: Majors in astrophysics are required to complete a series of introductory courses.

They may take either:

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physics 191</td>
<td>Physics I</td>
<td>3</td>
</tr>
<tr>
<td>Physics 191L</td>
<td>Physics I Laboratory</td>
<td>1</td>
</tr>
<tr>
<td>Physics 192</td>
<td>Physics II</td>
<td>3</td>
</tr>
<tr>
<td>Physics 192L</td>
<td>Physics II Laboratory</td>
<td>1</td>
</tr>
</tbody>
</table>

or (recommended for majors):

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physics 193</td>
<td>Focused Physics I</td>
<td>4</td>
</tr>
<tr>
<td>Physics 193L</td>
<td>Focused Physics I Laboratory</td>
<td>1</td>
</tr>
<tr>
<td>Physics 194</td>
<td>Focused Physics II</td>
<td>3</td>
</tr>
<tr>
<td>Physics 194L</td>
<td>Focused Physics II Laboratory</td>
<td></td>
</tr>
</tbody>
</table>

Required courses: In addition, majors in astrophysics are required to complete the following courses:

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physics 312</td>
<td>Introduction to Astrophysics</td>
<td>3</td>
</tr>
<tr>
<td>Physics 322</td>
<td>Physical Measurement Laboratory</td>
<td>3</td>
</tr>
<tr>
<td>Physics 411</td>
<td>Mechanics</td>
<td>3</td>
</tr>
<tr>
<td>Physics 421</td>
<td>Electricity and Magnetism</td>
<td>3</td>
</tr>
</tbody>
</table>

One quantum physics course, chosen from the following:

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physics 217</td>
<td>Introduction to Quantum Physics</td>
<td>3</td>
</tr>
<tr>
<td>Physics 318</td>
<td>Introduction to Quantum Physics II</td>
<td>3</td>
</tr>
<tr>
<td>Physics 471</td>
<td>Quantum Mechanics</td>
<td>3</td>
</tr>
</tbody>
</table>

One additional laboratory course, chosen from the following:

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physics 316</td>
<td>Optics and Wave Physics Laboratory</td>
<td>3</td>
</tr>
<tr>
<td>Physics 321</td>
<td>Electronics Laboratory</td>
<td>3</td>
</tr>
<tr>
<td>Physics 435</td>
<td>Nuclear and Radiochemistry Lab</td>
<td>3</td>
</tr>
</tbody>
</table>

Required advanced courses: In addition to the above requirements, students who are earning the astrophysics major are required to complete three advanced electives (300 level and above) from the following list. Students must receive letter grades for these advanced courses, and the course must be completed with a grade of at least a C-.

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physics 446</td>
<td>Galactic Astrophysics</td>
<td>3</td>
</tr>
<tr>
<td>Physics 456</td>
<td>Stellar Astrophysics</td>
<td>3</td>
</tr>
<tr>
<td>Physics 460</td>
<td>X-Ray &amp; Gamma-Ray Astrophysics</td>
<td>3</td>
</tr>
<tr>
<td>Physics 476</td>
<td>Astrophysics</td>
<td>3</td>
</tr>
<tr>
<td>Physics 478</td>
<td>From Black Holes to the Big Bang</td>
<td>3</td>
</tr>
</tbody>
</table>

They must also complete one additional course from the preceding list of five courses or one from the following list of courses:

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physics 422</td>
<td>Electricity and Magnetism II</td>
<td>3</td>
</tr>
<tr>
<td>Physics 474</td>
<td>Introduction to Particle Physics</td>
<td>3</td>
</tr>
<tr>
<td>Physics 477</td>
<td>Physics of Finite and Infinite Nuclear Systems</td>
<td>3</td>
</tr>
<tr>
<td>Physics 547</td>
<td>Intro to Elementary Particle Physics</td>
<td>3</td>
</tr>
<tr>
<td>Physics 558</td>
<td>Relativistic Astrophysics</td>
<td>3</td>
</tr>
<tr>
<td>EPSc 352</td>
<td>Earth Materials</td>
<td>5</td>
</tr>
<tr>
<td>EPSc 353</td>
<td>Earth Forces</td>
<td>4</td>
</tr>
<tr>
<td>EPSc 407</td>
<td>Remote Sensing</td>
<td>3</td>
</tr>
<tr>
<td>MEMS 3410</td>
<td>Fluid Mechanics</td>
<td>3</td>
</tr>
</tbody>
</table>

Math courses required for the astrophysics major:

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Math 131</td>
<td>Calculus I</td>
<td>3</td>
</tr>
<tr>
<td>Math 132</td>
<td>Calculus II</td>
<td>3</td>
</tr>
<tr>
<td>Math 233</td>
<td>Calculus III</td>
<td>3</td>
</tr>
<tr>
<td>Math 217</td>
<td>Differential Equations</td>
<td>3</td>
</tr>
</tbody>
</table>

Students who have completed Math 203 Honors Mathematics I and Math 204 Honors Mathematics II will have fulfilled the requirement for Math 131 Calculus I, Math 132 Calculus II, and Math 233 Calculus III.

Science-breadth requirement: Majors must select one of the following courses to satisfy the science-breadth requirement:

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chem 105</td>
<td>Introductory General Chemistry I</td>
<td>3</td>
</tr>
<tr>
<td>Chem 106</td>
<td>Introductory General Chemistry II</td>
<td>3</td>
</tr>
<tr>
<td>Chem 111A</td>
<td>General Chemistry I</td>
<td>3</td>
</tr>
<tr>
<td>Chem 112A</td>
<td>General Chemistry II</td>
<td>3</td>
</tr>
<tr>
<td>Chem 151</td>
<td>General Chemistry Laboratory I</td>
<td>2</td>
</tr>
<tr>
<td>Chem 152</td>
<td>General Chemistry Laboratory II</td>
<td>2</td>
</tr>
<tr>
<td>Chem 401</td>
<td>Physical Chemistry I</td>
<td>3</td>
</tr>
<tr>
<td>Chem 402</td>
<td>Physical Chemistry II</td>
<td>3</td>
</tr>
<tr>
<td>Chem 445</td>
<td>Instrumental Methods: Physical Chemistry</td>
<td>3</td>
</tr>
</tbody>
</table>
Students who have received credit for Chem 103 Advanced Placement Chemistry I and Chem 104 Advanced Placement Chemistry II can use them toward the Science-breadth requirement.

**Additional Information**

**Senior Honors:** Students are encouraged to work toward Latin honors (http://bulletin.wustl.edu/undergrad/artsci/honors/) (i.e., cum laude, magna cum laude, and summa cum laude). To qualify, students must meet the academic requirements of the college and successfully complete a suitable project under the supervision of a faculty member in the department. The project, whether experimental or theoretical, should demonstrate the student's capacity for independent work. Honors candidates must apply to the Undergraduate Studies Committee no later than the first day of classes of their senior year. The application should include a description of the proposed project, co-signed by the supervising professor. A written report of the completed work must be submitted to the committee by a March deadline. By enrolling in Physics 499, students may earn up to 6 units of credit for the honors project.

The physics department also offers physics majors the possibility to earn departmental distinctions. These distinctions require the same grade-point average cutoffs as Latin honors (http://bulletin.wustl.edu/undergrad/artsci/honors/) but are calculated exclusively from the grades in physics courses (i.e., all courses with the prefix L31). Three levels of distinction are offered: 1) highest distinction; 2) high distinction; and 3) distinction. The highest and high distinctions require at least one semester of undergraduate research and a senior thesis describing the results; these distinctions are limited to the top 15% (highest distinction) and the top 15% to 50% (high distinction) of the physics majors in their senior year as ranked by their GPA in the physics courses. Students who meet the GPA cutoff but who do not undertake undergraduate research and a senior thesis may only receive the third level of distinction.

**Minors**

**The Minor in Physics**

**Required introductory courses:** Minors in physics are required to complete a series of introductory courses.

They may take either:

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<tr>
<td>Physics 191</td>
<td>Physics I</td>
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<td>Physics 191L</td>
<td>Physics I Laboratory</td>
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<td>Physics 192</td>
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<td>Physics 193</td>
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<td>Physics 193L</td>
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**Required courses:** In addition, minors in physics are required to complete the following courses:

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<th>Code</th>
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<tr>
<td>Physics 217</td>
<td>Introduction to Quantum Physics</td>
<td>3</td>
</tr>
<tr>
<td>Physics 318</td>
<td>Introduction to Quantum Physics II</td>
<td>3</td>
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**Elective courses:** Minors must take at least one additional course at the 300 level or above (with the exception of Physics 303, Physics 304, Physics 341, Physics 342, Physics 441, Physics 442, Physics 499 and Physics 500) with a grade of C- or better.

**The Minor in Astrophysics and Astroparticle Physics**

**Required introductory courses:** Minors in astrophysics and astroparticle physics are required to complete a series of introductory courses.

They may take either:

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<td>Physics 194L</td>
<td>Focused Physics II Laboratory</td>
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</table>

**Required courses:** In addition, minors in astrophysics and astroparticle physics are required to complete the following courses:
**Physics (12/03/21)**

**Code**  | **Title**                                | **Units**
---|-------------------------------------------|---
Physics 217 | Introduction to Quantum Physics          | 3  
Physics 312 | Introduction to Astrophysics              | 3  

Minors must also take two of the following seven courses:

**Code**  | **Title**                                | **Units**
---|-------------------------------------------|---
Physics 318 | Introduction to Quantum Physics II       | 3  
Physics 446 | Galactic Astrophysics                     | 3  
Physics 456 | Stellar Astrophysics                      | 3  
Physics 460 | X-Ray & Gamma-Ray Astrophysics            | 3  
Physics 474 | Introduction to Particle Physics          | 3  
Physics 476 | Astrophysics                              | 3  
Physics 478 | From Black Holes to the Big Bang          | 3  

**The Minor in Biomedical Physics**

**Required Courses:** Minors in biomedical physics are required to complete a series of introductory courses.

They may take either:

**Code**  | **Title**                                | **Units**
---|-------------------------------------------|---
Physics 191 | Physics I                                | 3  
Physics 191L | Physics I Laboratory                      | 1  
Physics 192 | Physics II                               | 3  
Physics 192L | Physics II Laboratory                     | 1  

or:

**Code**  | **Title**                                | **Units**
---|-------------------------------------------|---
Physics 193 | Focused Physics I                         | 4  
Physics 193L | Focused Physics I Laboratory              | 1  
Physics 194 | Focused Physics II                        | 3  
Physics 194L | Focused Physics II Laboratory             | 3  

**Elective courses:** Minors must take two of the following four courses:

**Code**  | **Title**                                | **Units**
---|-------------------------------------------|---
Physics 350 | Physics of the Brain                      | 3  
Physics 354 | Physics of Living Systems (or Physics 454)| 3  
Physics 355 | Physics of Vision                         | 3  
Physics 481 | Critical Analysis of Scientific Data      | 3  

One of the following four laboratory courses:

**Code**  | **Title**                                | **Units**
---|-------------------------------------------|---
Physics 316 | Optics and Wave Physics Laboratory        | 3  
Physics 321 | Electronics Laboratory                    | 3  
Physics 322 | Physical Measurement Laboratory           | 3  
Physics 360 | Biophysics Laboratory                     | 3  

**Additional Information**

This is a minor for students interested in the discussion and application of methods and techniques from physics to topics in the area of biology and medicine. The program may be of interest to the pre-medicine student or the research-oriented science major.

**Courses**


**L31 Physics 105 General Physics**

Credit 4 units.

**L31 Physics 117A General Physics I**

Calculus-based introduction to the concepts, laws, and structure of physics. The course is taught in a lecture-based style and requires students to complete weekly homework assignments. Topics include kinematics, Newton's laws, energy, linear momentum, angular momentum, the conservation laws, gravitational force, harmonic motion, wave motion and interference, sound, and special relativity. Concurrent registration in a Physics 117A lab section is required. Prerequisite: Previous or concurrent enrollment in Calculus I (Math 131) is required; previous or concurrent enrollment in Calculus II (Math 132) strongly recommended. Credit may not be obtained for both Physics 117A and Physics 197 and students may not simultaneously enroll in both courses.

Credit 4 units. A&S IQ: NSM, AN Arch: NSM Art: NSM BU: SCI

**L31 Physics 125A Solar System Astronomy**

Designed for the nonscience major; this course deals with the planets, their moons and rings, comets, meteorites and interplanetary dust particles. In order to understand both classical astronomy and the results obtained from modern telescopes and the space program, basic scientific ideas (including optics and the laws of motion) are reviewed first. There also is some discussion of astronomical history to show how we have arrived at our present ideas of the structure and evolution of the solar system. Prerequisites: high school algebra and trigonometry or concurrent enrollment in Math 131. Credit 3 units. A&S IQ: NSM, AN Arch: NSM Art: NSM BU: SCI

**L31 Physics 126A Stars, Galaxies and Cosmology**

Intended as a general survey for the nonscience major. Topics include the structure and evolution of stars, such as red giants, white dwarfs, neutron stars, pulsars and black holes; galaxies and quasars; cosmology and the Big Bang theory. Prerequisites: high school algebra and trigonometry, or concurrent enrollment in Math 131. Credit 3 units. A&S IQ: NSM, AN Arch: NSM Art: NSM BU: SCI
L31 Physics 141 Selected Topics in Physics I
Topics of special interest (e.g., superconductivity, quasicrystals, neural networks, chaos, etc.) may be studied under the supervision of a faculty member, variously by lectures, seminars or individual study or research. Students hoping to arrange such a course must prepare a proposal and secure consent to undertake direction of the course from a faculty member and finally secure approval of the department chair.
Credit variable, maximum 3 units. A&S IQ: NSM Art: NSM BU: SCI

L31 Physics 142 Selected Topics in Physics I
Topics of special interest (e.g., holography, relativity, nuclear power, computer applications in physics, etc.) may be studied under the supervision of a faculty member, variously by lectures, seminars or individual study or research. Students hoping to arrange such a course must prepare a proposal and secure the instructor’s consent to undertake direction of the course from a faculty member and finally secure approval of the department chair.
Credit variable, maximum 3 units. A&S IQ: NSM Art: NSM BU: SCI

L31 Physics 171A Physics and Society
Introduction to physics as it applies to the world we have built for ourselves. Energy as a unifying principle of physics and society’s use of energy. Atoms, heat, and power. Essentials of conventional and alternative forms of energy. Nuclear energy, including radiation, waste, and weapons. Global climate change. Credit 3 units. A&S IQ: NSM, AN Arch: NSM Art: NSM BU: SCI

L31 Physics 191 Physics I
This is a calculus-based introduction to the concepts, laws, and structure of physics. Topics include kinematics, Newton’s laws, energy, linear momentum, angular momentum, the conservation laws, gravitational force, harmonic motion, wave motion and interference, sound, and special relativity. A daily regimen of homework and reading as well as weekly homework assignments, small-group problem-solving exercises, and active class participation are integral parts of this course. Prerequisite: Previous or concurrent enrollment in Calculus I (Math 131) is strongly recommended. Students may not receive credit for more than one of Physics 117A, Physics 191, and Physics 197.
Credit 3 units. A&S IQ: NSM, AN Arch: NSM Art: NSM BU: SCI

L31 Physics 191F Physics I — First-Years Only
This section of Physics 191 is for rising seniors, juniors, and sophomores only. Any non-first-year student enrolled in this section will be removed from the course. First-year students should enroll in Physics 191F. This is a calculus-based introduction to the concepts, laws, and structure of physics. Topics include kinematics, Newton’s laws, energy, linear momentum, angular momentum, the conservation laws, gravitational force, harmonic motion, wave motion and interference, sound, and special relativity. Two evening exams are required, followed by a required final exam. Prerequisite: Previous or concurrent enrollment in Calculus I (Math 131) is required; previous or concurrent enrollment in Calculus II (Math 132) is strongly recommended. A combination of Physics 191 and Physics 191L is a replacement for Physics 197. Students may not receive credit for more than one of Physics 117A, Physics 191, and Physics 197.
Credit 3 units. A&S IQ: NSM, AN Arch: NSM Art: NSM BU: SCI

L31 Physics 191L Physics I Laboratory
Laboratory experience is an integral component of introductory physics. It is designed to provide a hands-on opportunity to explore concepts introduced in the lecture course and to develop careful measurement and documentation skills. Prerequisite/corequisite: Physics 191. Students may not receive credit for Physics 191L if they have already received credit for Physics 117A or 197.
Credit 1 unit. Arch: NSM

L31 Physics 191U Physics I — Sophomores, Juniors, and Seniors Only
This section of Physics 191 is for rising seniors, juniors, and sophomores only. Any first-year student enrolled in this section will be removed from the course. First-year students should enroll in Physics 191F. This is a calculus-based introduction to the concepts, laws, and structure of physics. Topics include kinematics, Newton’s laws, energy, linear momentum, angular momentum, the conservation laws, gravitational force, harmonic motion, wave motion and interference, sound, and special relativity. Two evening exams are required, followed by a required final exam. Prerequisite: Previous or concurrent enrollment in Calculus I (Math 131) is required; previous or concurrent enrollment in Calculus II (Math 132) is strongly recommended. A combination of Physics 191 and Physics 191L is a replacement for Physics 197. Students may not receive credit for more than one of Physics 117A, Physics 191, and Physics 197.
Credit 3 units. A&S IQ: NSM, AN Arch: NSM Art: NSM BU: SCI

L31 Physics 192 Physics II
Continuation of Physics 191. Calculus-based introduction to concepts, laws, and structure of physics. Topics include electromagnetic forces and fields, direct current circuits, capacitance and inductance, electromagnetic radiation, light, physical optics, interference and diffraction, early quantum theory, and nuclear physics. A daily regimen of homework and reading as well as weekly homework assignments, small-group problem-solving exercises, and active class participation are integral parts of this course. Prerequisite: Physics 191, Physics 197, or Physics 117A; Calculus I (Math 131); previous or concurrent enrollment in Calculus II (Math 132) is very strongly recommended. Students may not receive credit for more than one of Physics 118A, Physics 192, and Physics 198.
Credit 3 units. A&S IQ: NSM, AN BU: SCI

L31 Physics 192L Physics II Laboratory
Laboratory experience is an integral component of Introductory Physics. It is designed to provide a hands-on opportunity to explore concepts introduced in the lecture course and to develop careful measurement and documentation skills. Prerequisite/corequisite: Physics 192. Students who have taken Physics 118 or Physics 198 may not receive credit for Physics 192L.
Credit 1 unit.
L31 Physics 193 Focused Physics I
Physics 193 is the first part of a two-semester calculus-based introduction to physics. The course is an advanced first-year course in classical mechanics, taught at a more sophisticated level than Physics 191. The approach is that of an upper-division physics course, with more emphasis on underlying formal structure rather than breadth of topics. The main goal is to provide in-depth coverage of the physical laws that govern the motion of objects, forces, and forms of energy in mechanical systems as well as an introduction to special relativity. The course is particularly addressed to students considering a physics- or mathematics-heavy science or engineering major. Corequisite: Math 132 or equivalent.
Credit 3 units. A&S IQ: AN, Arch: NSM; SCI; NSM; AN

L31 Physics 193L Focused Physics I Laboratory
Laboratory experience is an integral component of Introductory Physics. It is designed to provide a hands-on opportunity to explore concepts introduced in the lecture course and to develop careful measurement and documentation skills. Required prerequisite or co-requisite: Physics 191. Students may not receive credit for Physics 191L if they have already received credit for 117A or 197
Same as L31 Physics 191L
Credit 1 unit. Arch: NSM

L31 Physics 201 Honors Problem Solving I
This is a problem-solving course for students considering a physics- or mathematics-heavy major. The problems we will focus on will be more difficult and sophisticated than those encountered in Physics 197. However, the content will be tightly linked to the weekly schedule of Physics 197, and the course will be taught by a Physics 197 instructor. This course is for incoming first-year students and rising sophomores. Prerequisites: concurrent enrollment in Physics 197 or AP physics and permission of the instructor.
Credit 1 unit. Arch: NSM

L31 Physics 204 Honors Problem Solving II
This is the second semester of a problem-solving course for students considering a physics- or mathematics-heavy major. The problems we will focus on will be more difficult and sophisticated than those encountered in Physics 192. However, the content will be tightly linked to the weekly schedule of Physics 192, and the course will be taught by a Physics 192 instructor. This course is for incoming first-year students and rising sophomores. Prerequisite: previous enrollment in Physics 201, concurrent enrollment in Physics 192, or permission of the instructor.
Credit 1 unit.

L31 Physics 205 General Physics I
This course is the first semester of a two-semester, calculus-based introductory physics course. In this semester, we will study the principles of Newtonian mechanics and their application to various physical systems. The material we learn this semester will serve as a basis for topics we will study in the second semester, such as electromagnetism. The aim of this course is to give you a robust introduction to the fundamentals of physics. Studying physics will also give you a better insight into other subjects like chemistry. The analytic techniques we develop will have a wide range of availability. Prerequisite: previous or concurrent enrollment in Calculus I.
Credit 3 units. A&S IQ: AN

L31 Physics 205L General Physics I Lab
The laboratory experience is an integral component of Introductory Physics. It is designed to provide a hands-on opportunity to explore concepts introduced in the lecture course and to develop careful measurement and documentation skills. Prerequisite or Corequisite: Physics 205.
Credit 1 unit.

L31 Physics 216 Introduction to Relativity: The Special Theory
Introduction to the special and general theories of relativity. Einstein’s postulates of the principle of relativity and the constancy of the speed of light. Simple kinematics and dynamics: simultaneity, time dilation, space-time diagrams, twin and other “paradoxes.” E=mc², laws of motion. Elements of general relativity: curved spacetime, experimental tests, black holes, gravitational waves. Prerequisite: Physics 117A, Physics 197 or permission of the instructor.
Credit 1 unit. A&S IQ: AN, Arch: NSM; AN; NSM; BSU; SCI

L31 Physics 217 Introduction to Quantum Physics
Theoretical and experimental basis for quantum mechanics, following the historical development of 20th-century physics. Failure of classical physics; the Bohr theory of the atom; the Heisenberg uncertainty principle; the Schroedinger equation; atomic and molecular structure. Prerequisites: Physics 117A and 118A or Physics 197 and 198.
Credit 3 units. A&S IQ: NSM, Arch: NSM; AN; BSU; SCI

L31 Physics 241 Selected Topics in Physics II
Topics of special interest (e.g., superconductivity, quasicrystals, neural networks, chaos, etc.) may be studied under the supervision of a faculty member, variously by lectures, seminars or individual study or research. Students hoping to arrange such a course must prepare a proposal and secure consent to undertake direction of the course from a faculty member and finally secure approval of the department chair.
Credit variable, maximum 3 units. A&S IQ: AN, Arch: NSM; AN; BSU; SCI

L31 Physics 242 Selected Topics in Physics II
Topics of special interest (e.g., holography, relativity, nuclear power, computer applications in physics, etc.) may be studied under the supervision of a faculty member, variously by lectures, seminars or individual study or research. Students hoping to arrange such a course must prepare a proposal and secure the instructor’s consent to undertake direction of the course from a faculty member and finally secure approval of the department chair.
Credit variable, maximum 3 units. A&S IQ: AN, Arch: NSM; AN; BSU; IS

L31 Physics 312 Introduction to Astrophysics
This course covers the physics needed for higher-level astrophysics courses, and is a requirement for those courses. Furthermore, it gives a first introduction to several topics in modern astrophysics, including stars (stellar structure and evolution), compact objects (neutron stars and black holes),
galaxies (galactic structure), and cosmology. The course should be taken by everybody interested in astrophysics. Prerequisite: Physics 117A and 118A; or Physics 197 and 198; or permission of instructor.
Credit 3 units. A&S IQ: NSM Arch: NSM Art: NSM BU: SCI

L31 Physics 316 Optics and Wave Physics Laboratory
Introduction to optics and to treatment of experimental data. Experiments and lectures on refraction, interference, diffraction, polarization and coherence properties of waves with emphasis on light. Data analysis using statistical methods. Prerequisites: Physics 117A–Physics 118A or Physics 197–Physics 198.
Credit 3 units. A&S IQ: NSM Arch: NSM Art: NSM BU: SCI

L31 Physics 318 Introduction to Quantum Physics II
Application of elementary quantum principles to atomic and molecular physics, solid-state physics, and nuclear and particle physics. Prerequisite: Physics 217.
Credit 3 units. A&S IQ: NSM, AN Arch: NSM Art: NSM BU: SCI

L31 Physics 321 Electronics Laboratory
Elements of linear and nonlinear circuits, amplifiers, feedback, with applications in experimental physics. Prerequisite: Physics 118A, Physics 198 or permission of instructor. Two three-hour laboratories and two one-hour lectures a week.
Credit 3 units. A&S IQ: NSM, AN Arch: NSM Art: NSM BU: SCI

L31 Physics 322 Physical Measurement Laboratory
A variety of classical and modern experiments in physics, including five experiments in nuclear radiation. Use of computers in experiment control, data acquisition, and data analysis. Development of skills in writing lab notebooks and formal reports and giving short oral presentations on experiments. Two laboratory periods each week. Prerequisites: Physics 217 or permission of instructor; junior- or senior-level standing.
Credit 3 units. A&S IQ: NSM, AN, WI Arch: NSM Art: NSM BU: SCI EN: BME T, DU, SU, TU

L31 Physics 323 Selected Topics in Physics III
Topics of special interest (e.g., superconductivity, quasicrystals, neural networks, chaos, etc.) may be studied under the supervision of a faculty member, variously by lectures, seminars or individual study or research. Students hoping to arrange such a course must prepare a proposal and secure consent to undertake direction of the course from a faculty member and finally secure approval of the department chair.
Credit variable, maximum 3 units. A&S IQ: NSM Arch: NSM Art: NSM BU: SCI

L31 Physics 344 Energy and Environmental Physics
This intermediate-level course applies basic physics principles to this increasingly important area. It is designed for all science and engineering majors with an interest in energy and environmental issues. Topics covered include population trends, fossil fuel use, renewable energy sources, energy storage strategies and climate change. Particular emphasis is given to the use of the fundamental laws of physics, such as energy conservation, as well as more general concepts such as local and global stability, chaotic behavior, probability and risk. The aim of the course is the development of analytical skills and familiarity with important concepts, in order to enable an independent and informed view of environmental problems and possible solutions. A one-year introductory physics class on the level of Physics 117–118 or 197–198 is required. This course also may be taken as Physics 444, which requires an additional independent project.
Credit 3 units. A&S IQ: NSM, AN Arch: NSM Art: NSM BU: SCI

L31 Physics 350 Physics of the Brain
Concepts and techniques of physics are applied to study the functioning of neurons and neuronal circuits in the brain. Neurons and neural systems are modeled at two levels: (1) at the physical level, in terms of the electrical and chemical signals that are generated and transmitted, and (2) at the information-processing level, in terms of the computational tasks performed. Specific topics include: (1) neuronal electrophysiology, neural codes, neural plasticity, sensory processing, neural network architectures and learning algorithms, and neural networks as dynamical and statistical systems. Course grade is based primarily on an individualized term project. Prerequisites: Physics 117A–118A, Physics 197–198, or permission of the instructor.
Credit 3 units. A&S IQ: NSM Arch: NSM Art: NSM BU: SCI EN: BME T, SU, TU

L31 Physics 351 Introduction to Biomedical Physics
Principles and application of key physical methods used in the diagnosis and treatment of diseases, and in biomedical research. Topics include interaction of radiation with living systems; fundamentals of optical and electron microscopy; imaging via X-rays, magnetic resonance and ultrasound; and electrical properties of organs and cells. Prerequisite: Physics 117A–118A or Physics 197–198.
Credit 3 units. Arch: NSM Art: NSM BU: SCI EN: BME T, TU

L31 Physics 352 Physics of Biomolecules
This course emphasizes the application of physical laws and concepts in understanding biomolecules and their interactions, and in developing tools to investigate their biological properties and functionalities. Topics include (1) a general introduction to biomolecules and cells, (2) physics of biopolymers as modeled by stochastic analyses, (3) transport processes in biological systems including diffusion, reaction kinetics and "life at low Reynolds number," and (4) the physics of fluorescence and its contemporary applications to dynamics of biomolecules, such as optical tweezers. Prerequisite: Physics 117–118 or Physics 197–198. Some familiarity with thermodynamics; Chem 111A–112A recommended.
Credit 3 units. A&S IQ: NSM, AN Arch: NSM
L31 Physics 354 Physics of Living Systems
One of the grand challenges in contemporary biophysics is placing our understanding of cellular systems on a firm quantitative footing. How does the collective activity of molecules enable the cell to sense its environment, make decisions, grow and develop? This course, aimed at physical and life science students, will serve as an introduction to the physical principles and mathematical techniques underlying the analysis of systems and synthetic biology. Topics will include modeling gene and signaling networks, the regulation of intracellular structures, and pattern formation in development. Students in this course can expect to learn both analytical and computer simulation approaches to fundamental problems in biology, biophysics, and biotechnology. Graduate students will explore the subject in more depth. Prerequisites: Physics 117A-118A or Physics 197-198 or Math 217 or Math 309, or permission of instructor. Credit 3 units. A&S IQ: NSM Arch: NSM BU: SCI EN: BME T, TU

L31 Physics 355 Physics of Vision
How do the eyes capture an image and convert it to neural messages that ultimately result in visual experience? This lecture and demonstration course covers the physics of how we see. The course is addressed to physics, premedical and life-sciences students with an interest in biophysics. Topics include physical properties of light, evolution of the eyes, image formation in the eye, image sampling with an array of photoreceptors, transducing light into electrical signals, color coding, retinal organization, computing with nerve cells, compressing the 3-D world into optic nerve signals, inferring the 3-D world from optic nerve signals, biomechanics of eye movement, engineered vision in machines. The functional impact of biophysical mechanisms for visual experience is illustrated with psychophysical demonstrations. Corequisite: Physics 117A, Physics 197 or permission of instructor. Credit 3 units. A&S IQ: NSM Arch: NSM Art: NSM BU: SCI EN: BME T, SU, TU

L31 Physics 360 Biophysics Laboratory
This laboratory course consists of "table-top" experiments in biological physics that are designed to introduce the student to concepts, methods and biological model systems in biophysics. Most experiments combine experimentation with computer simulations. The list of available experiments includes electrophysiology, human bioelectricity, optical tweezers, ultrasonic imaging, mass spectrometer and viscosity measurements. Prerequisites: prior completion of Physics 117A–118A, Physics 197–198 or permission of instructor. Credit 3 units. A&S IQ: NSM, AN Arch: NSM Art: NSM

L31 Physics 400 Physical Science in 12 Problems
Exercises related to general chemistry, classical mechanics, quantum mechanics, statistical mechanics, thermodynamics, and kinetics will be solved with numerical software. Each exercise will be accompanied by a lecture, a software template solving a problem, and a related take-home problem. The software will allow us to focus on and treat in a transparent fashion physical problems, without the unwieldy idealizations and contrivances found in textbooks. Prerequisites: General Chemistry; concurrent enrollment in Chem 401; and prior or concurrent enrollment in Physics 117A, Physics 197, or Physics 191L. Same as L07 Chem 400 Credit 1 unit. A&S IQ: NSM Arch: NSM Art: NSM BU: SCI

L31 Physics 411 Mechanics
Topics include the motion of a point particle, rotational motion, oscillation, gravitation and central forces, and Lagrangian and Hamiltonian formulation. Prerequisites: Phys 197-198, Math 217, or permission of instructor. Credit 3 units. A&S IQ: NSM Arch: NSM Art: NSM

L31 Physics 421 Electricity and Magnetism
Starting from Coulomb’s law, the Biot-Savart law and Faraday’s law, the electrical and magnetic fields are defined and applied. Maxwell’s equations are derived and their consequences, such as electromagnetic waves and relativity, are explored. Prerequisites: Physics 117A–118A or Physics 197–198, Math 217 or permission of instructor. Credit 3 units. A&S IQ: NSM, AN Arch: NSM Art: NSM BU: SCI EN: BME T, DU, SU, TU

L31 Physics 422 Electricity and Magnetism II
The second course in a two-part series covering the classical theory of electricity and magnetism leading to the derivation and application of Maxwell’s equation. Topics in electrodynamics including Faraday’s law, the displacement current and Maxwell’s equations in vacuum and in matter are covered. Electromagnetic waves and radiation, special relativity and relativistic electrodynamics also are discussed. Prerequisite: Physics 421 or permission of instructor. Credit 3 units. A&S IQ: NSM, AN Arch: NSM Art: NSM EN: BME T, DU, SU, TU

L31 Physics 427 Introduction to Computational Physics
What does it mean to solve a research problem using a computer? What is the difference between “someone ran a simulation” and an interesting research result? What skills are needed? Familiarity with a programming language is, of course, essential, but that is only the beginning. This course will focus on the methodology of computational research, touching also on topics in numerical analysis, statistics, and visualization. The format will combine lectures and hands-on experience with an emphasis on research-style small-group projects. Prerequisites: Physics 197/198, calculus, and familiarity with a programming language. Credit 3 units. A&S IQ: NSM Arch: NSM Art: NSM

L31 Physics 435 Nuclear and Radiochemistry Lab
Application of radiochemical techniques to problems in chemistry, physics, and nuclear medicine. Prerequisites: 3 units of physical chemistry and permission of instructor. One lecture hour and five hours of laboratory a week. Same as L07 Chem 435 Credit 3 units. A&S IQ: NSM Arch: NSM Art: NSM

L31 Physics 436 Introduction to the Atomic Nucleus
Introduction to the production and decay of radioactive nuclides, the structure and properties of nuclei, and the applications of nuclear and radiochemical techniques to current scientific problems. Prerequisites: one year each of chemistry, mathematics and physics. Same as L07 Chem 436 Credit 3 units. A&S IQ: NSM Arch: NSM Art: NSM
L31 Physics 441 Selected Topics in Physics IV
Topics of special interest (e.g., holography, relativity, nuclear power, computer applications in physics, etc.) may be studied under the supervision of a faculty member, variously by lectures, seminars or individual study or research. Students hoping to arrange such a course must prepare a proposal and secure the instructor's consent to undertake direction of the course from a faculty member and finally secure approval of the department chair.
Credit variable, maximum 3 units. A&S IQ: NSM Arch: NSM Art: NSM BU: SCI

L31 Physics 442 Selected Topics in Physics IV
Topics of special interest (e.g., holography, relativity, nuclear power, computer applications in physics, etc.) may be studied under the supervision of a faculty member, variously by lectures, seminars or individual study or research. Students hoping to arrange such a course must prepare a proposal and secure the instructor's consent to undertake direction of the course from a faculty member and finally secure approval of the department chair.
Credit variable, maximum 3 units. A&S IQ: NSM Arch: NSM Art: NSM BU: SCI

L31 Physics 446 Galactic Astrophysics
In these lectures, the focus is on the dynamics and statistical mechanics of a collection of stars, which is treated as a collisionless system. The course begins with a discussion of potential theory and proceeds to discuss the density and phase distributions of stars in star clusters and galaxies, thus leading to an understanding of the equilibria and stability of these systems. Topics such as Chandrasekhar's dynamical friction, galaxy formation, and dark matter will constitute the final topics of discussion.
Credit 3 units. A&S IQ: NSM Arch: NSM Art: NSM BU: SCI

L31 Physics 450 Physics of the Brain
Contents are the same as Physics 350. Also intended for graduate students. Includes a more sophisticated term project than Physics 350. Prerequisites: Physics 117A–118A or Physics 197–198, or permission of instructor.
Credit 3 units. A&S IQ: NSM Arch: NSM BU: SCI EN: BME T, SU, TU

L31 Physics 453 Topics in Theoretical Biophysics
Application of a range of physical models to biological systems. Topics include protein folding, self-assembling molecular systems, and mechanical properties of biological materials. Background material will be provided, but some exposure to statistical mechanics or thermodynamics is necessary. Prerequisite: experience with ordinary differential equations (as in Mathematics 217).
Credit 3 units. A&S IQ: NSM BU: SCI

L31 Physics 454 Physics of Living Systems
Contents are the same as Physics 354. Graduate students will explore the subject in more depth. Prerequisites: Physics 117A-118A or Physics 197-198 or Math 217 or Math 309, or permission of instructor.
Credit 3 units. A&S IQ: NSM Arch: NSM EN: TU

L31 Physics 455 Physics of Vision
Contents are the same as Physics 355. Also intended for graduate students. Includes a more sophisticated term project than Physics 355. Corequisite: Physics 117A , Physics 197 or permission of instructor.
Credit 3 units. A&S IQ: NSM Arch: NSM Art: NSM

L31 Physics 456 Stellar Astrophysics
The course Stellar Astrophysics discusses the physical processes that play a role inside stars. Relevant physical processes include emissions and absorption processes, radiation transfer, convective transfer, the weak and strong interactions, nuclear processes and nuclear burning, and the thermodynamics of equilibrium and non-equilibrium processes in stellar interiors. Subsequently, these processes are used to explain the structure and evolution of stars of different mass ranges. Finally, the course discusses endpoints of stellar evolution including white dwarfs, neutron stars, black holes, supernova explosions and gamma-ray burst. Prerequisites: Physics 312, Physics 318, or permission of instructor. Same as L31 Physics 556
Credit 3 units.

L31 Physics 460 X-Ray & Gamma-Ray Astrophysics
Observers started to use X-ray and gamma-rays in the ’60s and ’70s to explore the cosmos with high-energy photons. The sky looks dramatically different at these energies with bright flares from mass accreting black holes and gamma-ray bursts and large diffuse emission from supernova remnants and cosmic rays interacting with galactic matter and magnetic fields dominating the emission. This course gives a comprehensive overview of the underlying physics and observable phenomenology. Topics covered include the history of X-ray and gamma-ray astronomy, high-energy radiation processes, particle heating and acceleration, accretion physics, blast waves and shocks, black holes, neutron stars, supernova remnants, gamma-ray bursts, and galaxy clusters. Prerequisite: L31 Physics 312.
Credit 3 units. A&S IQ: NSM Arch: NSM

L31 Physics 463 Statistical Mechanics and Thermodynamics
Basic methods of classical and quantum statistical mechanics, thermodynamics and transport theory. Prerequisite: Physics 217 or permission of instructor.
Credit 3 units. A&S IQ: NSM, AN Arch: NSM Art: NSM

L31 Physics 471 Quantum Mechanics
Origins of quantum theory, wave packets and uncertainty relations, Schrödinger's equation in one dimension, step potentials and harmonic oscillators, eigenfunctions and eigenvalues, Schrödinger's equation in three dimensions, the hydrogen atom, symmetry, spin and the periodic table, approximation methods for time independent problems, quantum statistics. Prerequisite: Math 217, Physics 217, or permission of instructor.
Credit 3 units. A&S IQ: NSM Arch: NSM Art: NSM EN: BME T, SU, TU

L31 Physics 472 Solid State Physics
Crystal structures, binding energies, thermal properties, dielectrics, magnetism, free electron theory of metals, band theory, semiconductors, defects in solids. Prerequisite: Physics 471.
Credit 3 units. A&S IQ: NSM Arch: NSM Art: NSM

L31 Physics 474 Introduction to Particle Physics
Introduction to the standard model of particle physics, including symmetries, conservation laws, the weak interaction, the strong interaction, quark confinement and some more exotic ideas such as grand unified theories. Prerequisite: Physics 471.
Credit 3 units. A&S IQ: AN Arch: NSM Art: NSM

L31 Physics 476 Astrophysics
This Astrophysics course focuses on cosmic rays. Victor Hess discovered in 1912 that ionizing radiation impinges on the top of Earth’s atmosphere. Even though physicists have been studying cosmic rays (the ionizing radiation) for more than 100 years now with a fantastic repertoire of experimental and theoretical tools, cosmic rays never stop to surprise us, and cosmic ray physicists are still pushing the frontier of cosmic exploration in many ways. This course gives an introduction into this exciting topic covering historical and recent cosmic ray measurements at all energies, particle and antiparticle observations, and neutrino observations. The presently favored models of cosmic ray acceleration and transport are discussed in detail, and some topics of current interest are highlighted (including the production of particles and antiparticles by dark matter). The course also covers radio astronomy and highlights the clues about the origin of the cosmic rays that can be obtained from radio observations. Prerequisite: Physics 312 or permission of instructor.
Credit 3 units. A&S IQ: NSM Arch: NSM Art: NSM

L31 Physics 477 Physics of Finite and Infinite Nuclear Systems
Credit 3 units. A&S IQ: NSM Arch: NSM

L31 Physics 478 From Black Holes to the Big Bang
An introduction to general relativity. The goal is to illustrate important features of general relativity without the full-blown mathematics of Einstein’s equations by restricting attention to spherically symmetric spacetimes. Topics include: principle of equivalence; curved spacetime; spherical stars and black holes; the Big Bang model, observational cosmology. Prerequisite: Physics 411 or permission of instructor.
Credit 3 units. A&S IQ: NSM Arch: NSM Art: NSM

L31 Physics 481 Critical Analysis of Scientific Data
Data science is most commonly associated with topics in computer science. However, efficient algorithms, specific software packages, neural nets, and so on are only tools, and they are easily misused. In a research setting, working with data is primarily an exercise in critical thinking. The purpose of this interactive, hands-on course is to learn from mistakes by making them in a safe environment. After covering/reviewing probability theory, Bayesian inference, elements of information theory, and random matrix theory, the course will focus on case studies of real-world biological data, such as quantitative imaging data, next-generation sequencing (metagenomics), and neural recordings. These modules will involve the critical reading of research papers and working through puzzle-based assignments. The primary modules will be supplemented by shorter presentations on topics chosen by students. Fair warning: This is explicitly not a course on “big data” or machine learning, although students may choose to explore some of these topics in their presentations (required for credit). Experience with MatLab or Python strongly encouraged or will need to be acquired during the course. Open to undergraduates with prior programming experience and a quantitative background (Phys 197/198, Math 203 or similar; contact instructor if unsure). Experience with data or statistics not required. Course mimics a research environment, and undergraduates considering an academic research track are especially encouraged.
Credit 3 units. Arch: NSM Art: NSM BU: SCI

L31 Physics 482 Research Seminar
Designed to introduce students to current developments in physics and to research carried out by faculty. Topics vary each year. Each member of the department addresses their particular specialty. Interested undergraduates may take this seminar in their junior or senior year. Must be taken pass/fail.
Credit 1 unit. A&S IQ: NSM Arch: NSM Art: NSM

L31 Physics 499 Honors Program
Prerequisites: junior standing, an average grade of B or better, and permission of the chair of the department. Program and credit to be determined; maximum 6 units.
Credit variable, maximum 3 units.