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 advisor, 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**

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

**Associate Chair**

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

**Professors**

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

PhD, University of Chicago  
Experimental high-energy astrophysics

PhD, Harvard University  
Biophysics

PhD, Free University, Amsterdam  
Many-body theory

PhD, Cornell University  
Theoretical astrophysics
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PhD, University of California, Berkeley
Quantum information and materials

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PhD, University of California, Los Angeles
Theoretical condensed matter physics

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PhD, Brown University
Theoretical particle physics

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PhD, Massachusetts Institute of Technology
Theoretical condensed matter physics

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PhD, University of Cambridge
Biophysics

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PhD, Georgia Institute of Technology
Condensed matter and materials science

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PhD, University of California, Berkeley
Chemistry
Experimental nuclear physics

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PhD, Universitat Autònoma de Barcelona
Theoretical astroparticle physics and cosmology

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PhD, Columbia University
Condensed matter and materials science

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PhD, University of Maryland, College Park
Theoretical astroparticle physics and cosmology

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PhD, Universitat Autonoma de Barcelona
High-energy astrophysics, black holes, active galactic nuclei

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

Andrina Nicola
PhD, ETH Zurich
Cosmology and machine learning

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PhD, California Institute of Technology
Cosmochemistry, planetary science

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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
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Yajie Yuan
PhD, Stanford University
Theoretical high energy astrophysics

Chong Zu (https://physics.wustl.edu/people/chong-zu/)
PhD, Tsinghua University
Atomic, molecular and optical physics, condensed matter, quantum information

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Lecturer
Augusto Medeiros da Rosa (https://physics.wustl.edu/people/augusto-medeiros-da-rosa/)
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Research Professors
Sachiko Amari (https://physics.wustl.edu/people/sachiko-amari/)
PhD, Kobe University

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

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PhD, Vernadsky Institute of Cosmochemistry

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

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

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

Research Assistant Professors
Yuran Chen
PhD, Columbia University

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

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/)
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PhD, California Institute of Technology

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

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PhD, Washington University

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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-m-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>4</td>
</tr>
<tr>
<td>Physics 194L</td>
<td>Focused Physics II Laboratory</td>
<td>1</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 217</td>
<td>Introduction to Quantum Physics</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 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>
<tr>
<td>Physics 427</td>
<td>Introduction to Computational Physics</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 and may also include one upper level engineering class chosen from the following:

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESE 351</td>
<td>Signals and Systems</td>
<td>3</td>
</tr>
<tr>
<td>ESE 429</td>
<td>Basic Principles of Quantum Optics and Quantum Information</td>
<td>3</td>
</tr>
<tr>
<td>ESE 436</td>
<td>Semiconductor Devices</td>
<td>3</td>
</tr>
<tr>
<td>ESE 438</td>
<td>Applied Optics</td>
<td>3</td>
</tr>
<tr>
<td>ESE 441</td>
<td>Control Systems</td>
<td>3</td>
</tr>
<tr>
<td>ESE 482</td>
<td>Digital Signal Processing</td>
<td>3</td>
</tr>
<tr>
<td>ESE 531</td>
<td>Nano and Micro Photonics</td>
<td>3</td>
</tr>
<tr>
<td>ESE 532</td>
<td>Introduction to Nano-Photonic Devices</td>
<td>3</td>
</tr>
<tr>
<td>ESE 582</td>
<td>Fundamentals and Applications of Modern Optical Imaging</td>
<td>3</td>
</tr>
<tr>
<td>MEMS 3410</td>
<td>Fluid Mechanics</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.


<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>
<tr>
<td>Chem 103</td>
<td>Advanced Placement Chemistry I</td>
<td>3</td>
</tr>
<tr>
<td>Chem 104</td>
<td>Advanced Placement Chemistry II</td>
<td>3</td>
</tr>
<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>
<tr>
<td>CSE 131</td>
<td>Introduction to Computer Science</td>
<td>3</td>
</tr>
<tr>
<td>CSE 132</td>
<td>Introduction to Computer Engineering</td>
<td>3</td>
</tr>
<tr>
<td>CSE 247</td>
<td>Data Structures and Algorithms</td>
<td>3</td>
</tr>
<tr>
<td>EPSc 201</td>
<td>Earth and the Environment</td>
<td>4</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.
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 350</td>
<td>Physics of the Brain</td>
<td>3</td>
</tr>
<tr>
<td>Physics 450</td>
<td>Physics of the Brain</td>
<td>3</td>
</tr>
<tr>
<td>Physics 355</td>
<td>Physics of Vision</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 354</td>
<td>Physics of Living Systems</td>
<td>3</td>
</tr>
<tr>
<td>Physics 453</td>
<td>Topics in Theoretical Biophysics</td>
<td>3</td>
</tr>
<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 who want to have the biophysics track displayed on their transcript must inform the Department of Physics (https://physics.wustl.edu/biophysics-track-declaration-form/) at least one semester before their graduation date. Contact the Director of Undergraduate Studies (dus@physics.wustl.edu) with any questions.

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):

**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 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>4</td>
</tr>
<tr>
<td>Physics 194L</td>
<td>Focused Physics II Laboratory</td>
<td>1</td>
</tr>
</tbody>
</table>

**One additional laboratory course** must be 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 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>

**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). Students who declare an astrophysics major and who complete both Physics 125A Solar System Astronomy and Physics 126A Stars, Galaxies and Cosmology will be required to complete two advanced electives (300 level and above). They will choose courses 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>
</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>
<tr>
<td>CSE 131</td>
<td>Introduction to Computer Science</td>
<td>3</td>
</tr>
<tr>
<td>CSE 132</td>
<td>Introduction to Computer Engineering</td>
<td>3</td>
</tr>
<tr>
<td>CSE 247</td>
<td>Data Structures and Algorithms</td>
<td>3</td>
</tr>
<tr>
<td>EPSc 201</td>
<td>Earth and the Environment</td>
<td>4</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:

<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:

<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 II Laboratory</td>
<td></td>
</tr>
</tbody>
</table>

Required courses: In addition, minors 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 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>
</tbody>
</table>

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:

<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:

<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 II Laboratory</td>
<td></td>
</tr>
</tbody>
</table>

**Required courses:** In addition, minors in astrophysics and astroparticle 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 217</td>
<td>Introduction to Quantum Physics</td>
<td>3</td>
</tr>
<tr>
<td>Physics 312</td>
<td>Introduction to Astrophysics</td>
<td>3</td>
</tr>
</tbody>
</table>

Minors must also take two of the following seven courses:

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physics 318</td>
<td>Introduction to Quantum Physics II</td>
<td>3</td>
</tr>
<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 474</td>
<td>Introduction to Particle Physics</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>

The Minor in Biomedical Physics

**Required Courses:** Minors in biomedical 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:

<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></td>
</tr>
<tr>
<td>Physics 193L</td>
<td>Focused Physics I Laboratory</td>
<td></td>
</tr>
<tr>
<td>Physics 194</td>
<td>Focused Physics II</td>
<td></td>
</tr>
<tr>
<td>Physics 194L</td>
<td>Focused Physics II Laboratory</td>
<td></td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physics 350</td>
<td>Physics of the Brain</td>
<td>3</td>
</tr>
<tr>
<td>Physics 354</td>
<td>Physics of Living Systems (or Physics 454)</td>
<td>3</td>
</tr>
<tr>
<td>Physics 355</td>
<td>Physics of Vision</td>
<td>3</td>
</tr>
<tr>
<td>Physics 481</td>
<td>Critical Analysis of Scientific Data</td>
<td>3</td>
</tr>
</tbody>
</table>

One of the following four laboratory courses:

<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 322</td>
<td>Physical Measurement Laboratory</td>
<td>3</td>
</tr>
<tr>
<td>Physics 360</td>
<td>Biophysics Laboratory</td>
<td>3</td>
</tr>
</tbody>
</table>

**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 1001 First-Year Seminar: All About Black Holes**

Black holes are the Universe’s most extreme objects: they are so massive and compact that gravity bends space and time into a knot. The signature property of a black hole is that your can get in, but not out. In this first-year seminar, we discuss what is currently known about black holes, starting from Einstein's theories about space, time, and gravity, through the first observational evidence for black holes, to the latest images of the shadows cast by black holes taken with the largest telescopes on earth. This class is designed to bend your mind when figuring out why clocks run slower when approaching the edge of a black hole, what could be at the center of a black hole or even at the other side. At the same time, we will discuss the inner workings of the most advanced telescopes that astronomers have developed to study black holes, and the strategies astronomers employ to develop ever more sensitive instruments. Also expect a fair bit of astronomy in this class, when we discuss how black holes form, when and how they grow, and which roles they play in cosmic eco-systems such as the Milky Way Galaxy. This first-year seminar adopts a flipped class/socratic discussion structure. The students are asked to
read a wide variety of texts, including texts from the current literature, and to present and to discuss some of the material in class. The class assumes no background in math; at the same time, we will discuss some of the math that brings Einstein’s theories of space and time to life.

Credit 3 units. A&S: FYS A&S IQ: NSM, AN

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 130 Introduction to Mathematical and Computational Methods in Physics
This is a learning by doing course whose objective is for the students to learn practical methods for solving physics problems using mathematical and computational tools. The course gives an introduction to applied mathematics and basic computational tools and techniques used in contemporary scientific fields of research. The format of the course is highly interactive. Each course unit will be devoted to a specific activity, including a lecture from the instructor, working groups on solving analytical problems, and working groups on coding with Python. Prerequisite: Previous or concurrent Calculus I is recommended.

Credit 3 units. A&S IQ: NSM, AN Arch: NSM Art: NSM

L31 Physics 141 Selected Topics in Physics I
Topics of special interest (e.g., superconductivity, quasicrystals, neural networks, chaos) 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 apply for approval using the Physics independent study web form (https://physics.wustl.edu/independent-study/).

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) 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 apply for approval using the Physics independent study web form (https://physics.wustl.edu/independent-study/).

Credit 3 units. A&S IQ: NSM, AN Arch: NSM Art: NSM BU: SCI

L31 Physics 173 Physics of Sustainable Energy
Introduction to the physics of climate change and sustainable energy. This course is intended for students with little previous exposure to science or math. We will learn about the value of rough estimates and simple calculations. We will apply this approach to energy and power; atoms and heat; the history and basic modeling of earth’s climate; energy sources including fossil fuels, nuclear, and renewables. No prerequisites.

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 required; previous or concurrent enrollment in Calculus II (Math 132) 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 first-year students only. Any non-first-year students enrolled in this section will be removed from the course. Non-first-year students should enroll in Physics 191U. 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 193 and 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 electricity and magnetism, taught at a more sophisticated level than Physics 192. The approach is that of an upper-division physics course, with more emphasis on the underlying formal structure, rather than breadth of topics. The main goal is to provide an in-depth coverage of electromagnetism, DC and AC circuits using complex variables, and optics. The course is particularly addressed to students considering a physics or mathematics heavy science/engineering majors.
Credit 1 unit. Arch: NSM

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 194 Focused Physics II
Physics 194 is the second part of a two-semester calculus-based introduction to physics, with a co-requisite of Calculus III (Math 233 or its equivalent). The course is an advanced first-year course in electricity and magnetism, taught at a more sophisticated level than Physics 192. The approach is that of an upper-division physics course, with more emphasis on the underlying formal structure, rather than breadth of topics. The main goal is to provide an in-depth coverage of electromagnetism, DC and AC circuits using complex variables, and optics. The course is particularly addressed to students considering a physics or mathematics heavy science/engineering majors.
Credit 4 units. A&S IQ: NSM, AN BU: SCI

L31 Physics 194L Focused 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.
Same as L31 Physics 192L.
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 BU: SCI

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 206 General Physics II
Physics 206 is the second semester of a two-semester, calculus-based introductory physics course. In this semester, we build on what we learned in the first semester to explore more advanced topics like electromagnetism and optics. A strong understanding...
of the topics covered in Phys 205 is essential for this semester. 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 - Physics 205. Previous or concurrent in Calc II is recommended. Credit 3 units. A&S IQ: NSM, AN Arch: NSM Art: NSM BU: SCI

L31 Physics 206L General Physics II Lab
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: General Physics II. Credit 1 unit. Arch: NSM Art: NSM BU: SCI

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: Phys 191, Phys 193, Phys 197, or permission of instructor. Credit 1 unit. A&S IQ: NSM Arch: NSM Art: NSM BU: 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 Heisenberg uncertainty principle; the Schroedinger equation; atomic and molecular structure. Prerequisites: Phys 191-192 or Phys 193-194 or Phys 197-198 or Phys 205-206. Credit 3 units. A&S IQ: NSM, AN Arch: NSM Art: NSM BU: SCI

L31 Physics 242 Selected Topics in Physics II
Topics of special interest (e.g., holography, relativity, nuclear power, computer applications in physics) 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 apply for approval using the Physics independent study web form (https://physics.wustl.edu/independent-study/). Credit variable, maximum 3 units. A&S IQ: NSM Arch: NSM Art: NSM BU: 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. Prerequisites: Physics 191 and 192 or Physics 193 and 194 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: Phys 192, Phys 194, Phys 198, Phys 206, or permission of instructor. Two three-hour laboratories and two one-hour lectures per week. Credit 3 units. A&S IQ: NSM, AN Arch: NSM Art: NSM BU: SCI EN: BME T, DU, SU, TU

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: EN TU

L31 Physics 341 Selected Topics in Physics II
Topics of special interest (e.g., superconductivity, quasicrystals, neural networks, chaos) 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 apply for approval using the Physics independent study web form (https://physics.wustl.edu/independent-study/). Credit variable, maximum 3 units. A&S IQ: NSM Arch: NSM Art: NSM BU: SCI

L31 Physics 342 Selected Topics in Physics II
Topics of special interest (e.g., holography, relativity, nuclear power, computer application in physics) 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 apply for approval using the Physics independent study web form (https://physics.wustl.edu/independent-study/). Credit variable, maximum 3 units. A&S IQ: NSM 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 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: Phys
191-192 or Phys 193-194 or Phys 197-198 or Phys 205-206, 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. Prerequisites: Physics 191-192 or
Phys 193-194 or Physics 197-198 or Phys 205-206.
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 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 191-192 or
Phys 193-194 or Physics 197-198 or Phys 205-206. Some
familiarity with thermodynamics and Chemistry 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 191-192 or Phys 193-194 or
Physics 197-198 or Phys 205-206, 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: Physics 191-192 or Phys 193-194
or Physics 197-198 or Phys 205-206 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 presenting 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 and/or Physics, and prior or concurrent enrollment
in either Chem 401 or Phys 217. The lectures will be in person;
however, a complete set of taped lectures will also be available.
A remote help session will be scheduled at a mutually agreed-
upon time. There are no quizzes, exams or a final.
Same as L07 Chem 400
Credit 1 unit. A&S IQ: NSM Arch: NSM Art: NSM

L31 Physics 411 Mechanics
Motion of a point particle, rotational motion, oscillation,
gravitation and central forces, Lagrangian and Hamiltonian
formulation. Prerequisites: Physics 191-192 or Phys 193-194 or
Physics 197-198 or Phys 205-206, 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 191-192 or Phys 193-194 or Physics
197-198 or Phys 205-206, Math 217, or permission of instructor.
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 BU: SCI
EN: BME T, DU, SU, TU

L31 Physics 442 Selected Topics in Physics IV
Topics of special interest (e.g., holography, relativity, nuclear power, computer applications in physics) 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 apply for approval using the Physics independent study web form (https://physics.wustl.edu/independent-study/).
Credit variable, maximum 3 units. A&S IQ: NSM Arch: NSM Art: NSM

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 Phys 350. Also intended for graduate students. Includes a more sophisticated term project than Phys 350. Prerequisites: Physics 191-192 or Phys 193-194 or Physics 197-198 or Phys 205-206, Calculus, and familiarity with a programming language.
Credit 3 units. A&S IQ: NSM Arch: NSM Art: 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 Phys 354. Graduate students will explore the subject in more depth. Prerequisites: Physics 191-192 or Phys 193-194 or Physics 197-198 or Phys 205-206, or Math 217 or Math 309, or permission of instructor.
Credit 3 units. A&S IQ: NSM Arch: NSM BU: SCI EN: BME T, SU, TU

L31 Physics 455 Physics of Vision
Contents are the same as Phys 355. Also intended for graduate students. Includes a more sophisticated term project than Phys 355. Prerequisite: Physics 191, Phys 193, Phys 197, Phys 206, 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.
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 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 Art: 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, nextgeneration 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 apply for approval using the Physics independent study web form https://physics.wustl.edu/independent-study. Program and credit to be determined; maximum 6 units.
Credit variable, maximum 3 units.