Faculty and students in the Department of Biomedical Engineering have been breaking new ground in biomedical research for over 50 years, and we strive to continue this history of innovation and discovery every day. Some examples of biomedical engineering include instrumentation and systems for use in medical environments, health care delivery systems, therapeutic and prosthetic devices such as artificial organs and orthopedic implants, and the application of quantitative methods and engineering-based modeling to basic research in the biological sciences.

The Department of Biomedical Engineering offers three programs of study to prepare students to work in this area: an undergraduate program leading to a bachelor’s degree with a choice of B.S. or B.A., a master’s degree program, and a doctoral degree program.

Research in the department focuses on several general areas: biomedical imaging, cell and tissue engineering, computational biology, computational medicine, molecular and cellular systems biology, and systems neuroscience and neuroengineering.

Facilities
The center of gravity for the Department of Biomedical Engineering is the Traylor, Ross, Miller, and Smith research buildings on the campus of the School of Medicine. This location favors a close association with other basic medical science programs and provides access to the clinical environment of one of the nation’s top-ranked hospitals. The Homewood campus houses the Whitaker Biomedical Engineering Institute. The Whitaker Institute was established as a vital link between the School of Medicine and the Whiting School of Engineering. The vision of the institute is of an integrative research and education enterprise that provides leadership in moving biomedical engineering to the forefront of biomedical science and practice.

The general facilities of the Department of Biomedical Engineering include seminar rooms that allow broadcasting throughout the university, physiology teaching laboratories, a microfabrication laboratory, a cell and tissue teaching and research laboratory, a fully-staffed mechanical shop, and the department’s design studio - a premiere work space for students to brainstorm, design, and develop prototypes for solutions to real-world clinical and global health challenges.

Each faculty member maintains a well-equipped laboratory for research in his or her area of interest. A wide variety of equipment in these laboratories is available to students as their interests draw them into active participation in research.

The profoundly interdivisional nature of biomedical engineering education at Johns Hopkins provides students with a wide range of general university facilities. These include the Human Stem Cell Core facility, the Institute for Basic Biomedical Sciences Microscope Core facility, the Tissue Microarray Core facility, the Flow Cytometry Core Facility, the Genetics Resources Core Facility, the Transgenic Core Laboratory, the Welch Medical Library at the School of Medicine, the Eisenhower Library at the Homewood campus, and computing laboratories that are available on both campuses.

The mission of the undergraduate programs is to provide state-of-the-art biomedical engineering education to students in order that they may continue their education in graduate, medical, and professional schools or pursue careers in industry. To this end, our responsibility is as much to the future as it is to the present. Through a strong research and educational environment, we strive to empower our students to explore and define their own frontiers as well as instill the ethical principles that will foster rewarding professional endeavors. The B.S. in Biomedical Engineering degree program is accredited by the Engineering Accreditation Commission of ABET, http://www.abet.org.

The biomedical engineering program normally leads to the bachelor of science degree and requires at least 129 credits. The B.S. program is recommended for students who plan careers in engineering or who plan to attend graduate school in engineering. If a student wishes to take a more flexible program with less emphasis on engineering, a B.A. program is also available. Either the B.S. or the B.A. program can meet the needs of a student who plans graduate study in a nonengineering area.

The undergraduate program provides a strong foundation in mathematics, engineering, and science. It emphasizes preparation for advanced study in an area related to biomedical engineering and is broad enough to accommodate students who plan graduate work in biology, medicine, engineering, biophysics, physiology, or biomedical engineering.

Our fundamental aim is to instill a passion for learning, scientific discovery, innovation, entrepreneurial spirit, and societal impact in an extraordinary group of graduates who, because of their experiences in our program, will:

- continue to utilize and enhance their engineering and biological training to solve problems related to health and healthcare that are globally relevant and based on ethically sound principles.
- demonstrate leadership in their respective careers in biomedical engineering or interrelated areas of industry, government, academia, and clinical practice, and
- engage in life-long learning by continuing their education in graduate or professional school or through opportunities for advanced career or professional training.

Each student plans a curriculum suited to his or her goals with the assistance of a faculty advisor. Upon completion of the B.S. in biomedical engineering, students will demonstrate:

(a) an ability to apply knowledge of mathematics, science, and engineering
(b) an ability to design and conduct experiments, as well as to analyze and interpret data
(c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability
(d) an ability to function on multidisciplinary teams
(e) an ability to identify, formulate, and solve engineering problems
(f) an understanding of professional and ethical responsibility
(g) an ability to communicate effectively
(h) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context
(i) a recognition of the need for, and an ability to engage in life-long learning
(j) a knowledge of contemporary issues
(k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.
The program also encourages individual study and research and gives academic credit for them. Students are welcome to work in laboratories on the Homewood campus or at the Medical Institutions in East Baltimore.

**Bachelor of Science in Biomedical Engineering**

Students seeking the B.S. degree are encouraged to focus their studies on one of five subspecialties that incorporates traditional engineering disciplines and biomedical applications. See the Biomedical Engineering Undergraduate Advising Manual for specifics on focus areas, lists of recommended mathematics and engineering electives, limitations on credits for courses with overlapping material, and the design content of engineering courses.

**Requirements for the B.S. Degree**

(See also General Requirements for Departmental Majors (http://e-catalog.jhu.edu/undergrad-students/academic-policies/requirements-for-a-bachelors-degree/).

The B.S. degree in biomedical engineering requires 129 credits. The courses listed below must either be taken or passed by examination for advanced credit. Engineering, science, and mathematics courses may not be taken satisfactory/unsatisfactory. No more than 6 credits of engineering, science, or mathematics courses in which a grade of D was received may be counted.

**Basic Sciences (22 credits)**  

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>AS.171.101</td>
<td>General Physics:Physical Science Major I</td>
<td>4</td>
</tr>
<tr>
<td>or AS.171.107</td>
<td>General Physics for Physical Sciences Majors (AL)</td>
<td>4</td>
</tr>
<tr>
<td>AS.171.102</td>
<td>General Physics: Physical Science Major II</td>
<td>4</td>
</tr>
<tr>
<td>or AS.171.108</td>
<td>General Physics for Physical Science Majors (AL)</td>
<td>4</td>
</tr>
<tr>
<td>AS.173.111</td>
<td>General Physics Laboratory I</td>
<td>1</td>
</tr>
<tr>
<td>AS.173.112</td>
<td>General Physics Laboratory II</td>
<td>1</td>
</tr>
<tr>
<td>AS.030.101</td>
<td>Introductory Chemistry I</td>
<td>3</td>
</tr>
<tr>
<td>AS.030.102</td>
<td>Introductory Chemistry II</td>
<td>3</td>
</tr>
<tr>
<td>AS.030.105</td>
<td>Introductory Chemistry Laboratory I</td>
<td>1</td>
</tr>
<tr>
<td>AS.030.106</td>
<td>Introductory Chemistry Laboratory II</td>
<td>1</td>
</tr>
<tr>
<td>AS.030.205</td>
<td>Introductory Organic Chemistry I</td>
<td>4</td>
</tr>
</tbody>
</table>

**Mathematics (24 credits)**  

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>AS.110.108</td>
<td>Calculus I and Calculus II (For Physical Sciences and Engineering)</td>
<td>8</td>
</tr>
<tr>
<td>AS.110.202</td>
<td>Calculus III</td>
<td>4</td>
</tr>
<tr>
<td>or AS.110.211</td>
<td>Honors Multivariable Calculus</td>
<td>4</td>
</tr>
<tr>
<td>AS.110.201</td>
<td>Linear Algebra</td>
<td>4</td>
</tr>
<tr>
<td>or AS.110.212</td>
<td>Honors Linear Algebra</td>
<td>4</td>
</tr>
<tr>
<td>AS.110.302</td>
<td>Differential Equations and Applications</td>
<td>4</td>
</tr>
</tbody>
</table>

**EN.553.311** Probability and Statistics for the Biological Sciences and Engineering  

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>or EN.553.310</td>
<td>Probability &amp; Statistics</td>
<td>3-4</td>
</tr>
<tr>
<td>or EN.553.413</td>
<td>Applied Statistics and Data Analysis</td>
<td>3</td>
</tr>
<tr>
<td>or EN.553.430</td>
<td>Introduction to Statistics</td>
<td>3</td>
</tr>
<tr>
<td>or EN.553.431</td>
<td>Statistical Methods in Imaging</td>
<td>3</td>
</tr>
<tr>
<td>or EN.553.433</td>
<td>Monte Carlo Methods</td>
<td>3</td>
</tr>
<tr>
<td>or EN.560.348</td>
<td>Probability &amp; Statistics for Engineers</td>
<td>3</td>
</tr>
</tbody>
</table>

**Humanities and Social Sciences (18 credits)**  

These courses should form a coherent program, relevant to the student’s goals, with at least one course at the 300-level or higher. They should include:

- One course in which ethical and social issues related to technology or medicine is recommended.
- At least two semesters of writing-intensive courses.

**Biomedical Core Knowledge (35 credits)**

**What do biomedical engineers do?**

- EN.580.111 BME Modeling and Design 2
- EN.580.202 Bme In The Real World 1

**Molecular and cellular biology**

- EN.580.221 Molecules and Cells 4

**Creating, analyzing and simulating a linear or nonlinear system model from knowledge of the real biological system**

- EN.580.222 Systems and Controls 4
- EN.580.223 Models and Simulations 4

**Fundamental thermodynamic principles in biology**

- EN.580.321 Statistical Mechanics and Thermodynamics 4

**Engineering analysis of systems-level biology and physiology**

- EN.580.421 Systems Bioengineering I 4
- EN.580.423 Systems Bioengineering Lab I 2
- EN.580.422 Systems Bioengineering II 4
- EN.580.424 Systems Bioengineering Lab 2
- EN.580.429 Systems Bioengineering III 4

**Focus Area (21 credits)**

Each student is required to take one of five Biomedical Engineering focus areas.

**Design**

Among the technical elective courses offered, at least 6 credits must come from an approved list of design options.

**Computer Programming**

Select 1 of the following courses.

- EN.580.200 Introduction to Scientific Computing in BME using Python, Matlab, and R 3
- or EN.500.200 Computing for Engineers and Scientists 3
- or EN.510.202 Computation and Programming for Materials Scientists and Engineers 3
- or EN.553.383 Scientific Computing with Python 3
- or EN.553.385 Scientific Computing: Linear Algebra 3
- or EN.553.386 Scientific Computing: Differential Equations 3
- or EN.570.210 Computation/Math Modeling 3
- or EN.601.107 Introductory Programming in Java 3
- or EN.601.220 Intermediate Programming 3
- or AS.250.205 Introduction to Computing 3

**General Electives**

Students may choose at least two courses from any area.

* See Writing Requirement (http://e-catalog.jhu.edu/undergrad-students/academic-policies/requirements-for-a-bachelors-degree/#Writing_Requirement).
** Building on the foundation of this core curriculum, each student is required to take a cohesive sequence of advanced engineering encompassing one of five Biomedical Engineering focus areas. A student’s choice of focus area is made before the start of the junior year and is based on their experience with the Biomedical Engineering Core and their answers to the questions given below:

**Systems Biology**—“Do you want to focus on understanding at a fundamental level how biological systems work?”

**Sensors, Micro/Nano Systems, and Instrumentation**—“Do you want to build things that facilitate research or clinical medicine?”

**Cell/Tissue Engineering and Biomaterials**—“Do you want to create replacement cells, tissues, and organs?”

**Computational Bioengineering**—“Do you want to focus on the use of mathematical theory or computers to solve complex biological and medical problems?”

**Imaging**—“Do you want to develop new imaging technology to reveal how biological systems work or diagnose disease?”

Courses in a focus area must be taken for a total of 21 or more credits. At least 18 credits must come from the relevant upper-level engineering course list; a maximum of three credits from the non-upper-level engineering course list may be used. Please refer to www.bme.jhu.edu/undergraduate/resources.htm for applicable courses designed for each focus area by faculty members with research interests appropriate to the area; all faculty members are active participants in shaping the undergraduate curriculum.

*** Among the technical elective courses offered, at least 6 credits must come from an approved list of design options. There are many combinations of courses, programs and independent study opportunities to satisfy this requirement. This is discussed in detail in the Undergraduate Handbook. Please refer to http://www.bme.jhu.edu/undergraduate/documents/BME- Undergraduate-Handbook.pdf.

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**Cell/Tissue Engineering and Biomaterials Focus Area - Upper-Level Engineering Courses**

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN.510.311</td>
<td>Structure Of Materials</td>
<td>3</td>
</tr>
<tr>
<td>EN.510.312</td>
<td>Thermodynamics/Materials</td>
<td>3</td>
</tr>
<tr>
<td>EN.510.313</td>
<td>Mechanical Properties of Materials</td>
<td>3</td>
</tr>
<tr>
<td>EN.510.314</td>
<td>Electronic Properties of Materials</td>
<td>3</td>
</tr>
<tr>
<td>EN.510.315</td>
<td>Physical Chemistry of Materials II</td>
<td>3</td>
</tr>
<tr>
<td>EN.510.316</td>
<td>Biomaterials I</td>
<td>3</td>
</tr>
<tr>
<td>EN.510.403</td>
<td>Materials Characterization</td>
<td>3</td>
</tr>
<tr>
<td>EN.510.407</td>
<td>Biomaterials II: Host response and biomaterials applications</td>
<td>3</td>
</tr>
<tr>
<td>EN.510.415</td>
<td>The Chemistry of Materials Synthesis</td>
<td>3</td>
</tr>
<tr>
<td>EN.510.421</td>
<td>Nanoparticles</td>
<td>3</td>
</tr>
<tr>
<td>EN.510.422</td>
<td>Micro and Nano Structured Materials &amp; Devices</td>
<td>3</td>
</tr>
<tr>
<td>EN.510.426</td>
<td>Biomolecular Materials I - Soluble Proteins and Amphiphiles</td>
<td>3</td>
</tr>
<tr>
<td>EN.510.430</td>
<td>Biomaterials Lab</td>
<td>3</td>
</tr>
<tr>
<td>EN.510.435</td>
<td>Mechanical Properties of Biomaterials</td>
<td>3</td>
</tr>
<tr>
<td>EN.510.442</td>
<td>Nanomaterials Lab</td>
<td>3</td>
</tr>
<tr>
<td>EN.510.606</td>
<td>Polymer Chemistry &amp; Biology</td>
<td>3</td>
</tr>
<tr>
<td>EN.530.410</td>
<td>Biomechanics of the Cell</td>
<td>3</td>
</tr>
<tr>
<td>EN.530.426</td>
<td>Biofluid Mechanics</td>
<td>3</td>
</tr>
<tr>
<td>EN.530.436</td>
<td>Bioinspired Science and Technology</td>
<td>3</td>
</tr>
<tr>
<td>EN.530.446</td>
<td>Experimental Methods in Biomechanics</td>
<td>3</td>
</tr>
<tr>
<td>EN.530.448</td>
<td>Biosolid Mechanics</td>
<td>3</td>
</tr>
</tbody>
</table>

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**Cell/Tissue Engineering and Biomaterials Focus Area - Non Upper-Level Engineering Courses**

(maximum of 3 credits from this list may count in focus area)

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>AS.020.303</td>
<td>Genetics</td>
<td>3</td>
</tr>
<tr>
<td>AS.020.337</td>
<td>Stem Cells &amp; the Biology of Aging &amp; Disease</td>
<td>2</td>
</tr>
<tr>
<td>AS.020.363</td>
<td>Developmental Biology</td>
<td>3</td>
</tr>
<tr>
<td>AS.020.373</td>
<td>Develop Biology Lab</td>
<td>2</td>
</tr>
<tr>
<td>EN.580.112</td>
<td>BME Design Group</td>
<td>3</td>
</tr>
<tr>
<td>EN.580.211</td>
<td>BME Design Group</td>
<td>3</td>
</tr>
<tr>
<td>EN.580.212</td>
<td>BME Design Group</td>
<td>3</td>
</tr>
<tr>
<td>EN.580.311</td>
<td>BME Design Group</td>
<td>3</td>
</tr>
<tr>
<td>EN.580.312</td>
<td>BME Design Group</td>
<td>3</td>
</tr>
<tr>
<td>EN.580.411</td>
<td>BME Design Group</td>
<td>3</td>
</tr>
<tr>
<td>EN.580.412</td>
<td>BME Design Group</td>
<td>3</td>
</tr>
<tr>
<td>EN.580.580</td>
<td>Senior Design Project</td>
<td>3</td>
</tr>
<tr>
<td>EN.580.581</td>
<td>Senior Design Project</td>
<td>3</td>
</tr>
</tbody>
</table>
Students may use a maximum of 3 research credits as a non-upper-level engineering course.

**Computational Biology Focus Area - Upper-Level Engineering Courses**

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN.520.447</td>
<td>Information Theory</td>
<td>3</td>
</tr>
<tr>
<td>EN.540.303</td>
<td>Transport Phenomena I</td>
<td>3</td>
</tr>
<tr>
<td>EN.540.400</td>
<td>Project in Design: Pharmacokinetics</td>
<td>3</td>
</tr>
<tr>
<td>EN.540.409</td>
<td>Dynamic Modeling and Control</td>
<td>4</td>
</tr>
<tr>
<td>EN.540.414</td>
<td>Computational Protein Structure Prediction and Design</td>
<td>3</td>
</tr>
<tr>
<td>EN.553.361</td>
<td>Introduction to Optimization</td>
<td>4</td>
</tr>
<tr>
<td>EN.553.362</td>
<td>Introduction to Optimization II</td>
<td>4</td>
</tr>
<tr>
<td>EN.553.371</td>
<td>Cryptology and Coding</td>
<td>4</td>
</tr>
<tr>
<td>EN.553.391</td>
<td>Dynamical Systems</td>
<td>4</td>
</tr>
<tr>
<td>EN.553.400</td>
<td>Mathematical Modeling and Consulting</td>
<td>4</td>
</tr>
<tr>
<td>EN.553.413</td>
<td>Applied Statistics and Data Analysis</td>
<td>4</td>
</tr>
<tr>
<td>EN.553.420</td>
<td>Introduction to Probability</td>
<td>4</td>
</tr>
<tr>
<td>EN.553.426</td>
<td>Introduction to Stochastic Processes</td>
<td>4</td>
</tr>
<tr>
<td>EN.553.430</td>
<td>Introduction to Statistics</td>
<td>4</td>
</tr>
<tr>
<td>EN.553.431</td>
<td>Statistical Methods in Imaging</td>
<td>3</td>
</tr>
<tr>
<td>EN.553.436</td>
<td>Data Mining</td>
<td>4</td>
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<tr>
<td>EN.553.450</td>
<td>Computational Molecular Medicine</td>
<td>4</td>
</tr>
<tr>
<td>EN.553.463</td>
<td>Network Models in Operations Research</td>
<td>4</td>
</tr>
<tr>
<td>EN.553.472</td>
<td>Graph Theory</td>
<td>4</td>
</tr>
<tr>
<td>EN.553.492</td>
<td>Mathematical Biology</td>
<td>3</td>
</tr>
<tr>
<td>EN.553.720</td>
<td>Probability Theory I</td>
<td>4</td>
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<tr>
<td>EN.553.721</td>
<td>Probability Theory II</td>
<td>4</td>
</tr>
<tr>
<td>EN.553.730</td>
<td>Statistical Theory</td>
<td>4</td>
</tr>
<tr>
<td>EN.553.731</td>
<td>Statistical Theory II</td>
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</tr>
<tr>
<td>EN.580.420</td>
<td>Build-a-Genome</td>
<td>4</td>
</tr>
<tr>
<td>EN.580.431</td>
<td>Introduction to Computational Medicine I</td>
<td>4</td>
</tr>
<tr>
<td>EN.580.437</td>
<td>Neuro Data Design I</td>
<td>4</td>
</tr>
<tr>
<td>EN.580.438</td>
<td>Neuro Data Design II</td>
<td>4</td>
</tr>
<tr>
<td>EN.580.439</td>
<td>Models of the Neuron</td>
<td>4</td>
</tr>
<tr>
<td>EN.580.445</td>
<td>Networks</td>
<td>3</td>
</tr>
<tr>
<td>EN.580.448</td>
<td>Biomechanics of the Cell</td>
<td>3</td>
</tr>
<tr>
<td>EN.580.460</td>
<td>Theory of Cancer</td>
<td>3</td>
</tr>
<tr>
<td>EN.580.491</td>
<td>Learning Theory</td>
<td>3</td>
</tr>
<tr>
<td>EN.580.492</td>
<td>Build-a-Genome Mentor</td>
<td>4</td>
</tr>
<tr>
<td>EN.580.688</td>
<td>Foundations of Computational Biology &amp; Bioinformatics II</td>
<td>3</td>
</tr>
<tr>
<td>EN.580.689</td>
<td>Computational Personal Genomics</td>
<td>3</td>
</tr>
<tr>
<td>EN.580.694</td>
<td>Statistical Connectomics</td>
<td>3</td>
</tr>
<tr>
<td>EN.601.226</td>
<td>Data Structures</td>
<td>4</td>
</tr>
<tr>
<td>EN.601.229</td>
<td>Computer System Fundamentals</td>
<td>3</td>
</tr>
<tr>
<td>EN.601.315</td>
<td>Databases</td>
<td>3</td>
</tr>
<tr>
<td>EN.601.320</td>
<td>Parallel Programming</td>
<td>3</td>
</tr>
<tr>
<td>EN.601.325</td>
<td>Declarative Methods</td>
<td>3</td>
</tr>
<tr>
<td>EN.601.350</td>
<td>Introduction to Genomic Research</td>
<td>3</td>
</tr>
<tr>
<td>EN.601.402</td>
<td>Digital Health and Biomedical Informatics</td>
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</tr>
<tr>
<td>EN.601.421</td>
<td>Object Oriented Software Engineering</td>
<td>3</td>
</tr>
<tr>
<td>EN.601.433</td>
<td>Intro Algorithms</td>
<td>3</td>
</tr>
<tr>
<td>EN.601.434</td>
<td>Randomized and Big Data Algorithms</td>
<td>3</td>
</tr>
<tr>
<td>EN.601.443</td>
<td>Security &amp; Privacy in Computing</td>
<td>3</td>
</tr>
<tr>
<td>EN.601.447</td>
<td>Computational Genomics: Sequences</td>
<td>3</td>
</tr>
<tr>
<td>EN.601.448</td>
<td>Computational Genomics: Data Analysis</td>
<td>3</td>
</tr>
<tr>
<td>EN.601.452</td>
<td>Computational Biomedical Research</td>
<td>3</td>
</tr>
<tr>
<td>EN.601.455</td>
<td>Computer Integrated Surgery I</td>
<td>4</td>
</tr>
<tr>
<td>EN.601.456</td>
<td>Computer Integrated Surgery II</td>
<td>3</td>
</tr>
<tr>
<td>EN.601.461</td>
<td>Computer Vision</td>
<td>3</td>
</tr>
<tr>
<td>EN.601.463</td>
<td>Algorithms for Sensor-Based Robotics</td>
<td>3</td>
</tr>
<tr>
<td>EN.601.464</td>
<td>Artificial Intelligence</td>
<td>3</td>
</tr>
<tr>
<td>EN.601.465</td>
<td>Natural Language Processing</td>
<td>4</td>
</tr>
<tr>
<td>EN.601.466</td>
<td>Information Retrieval and Web Agents</td>
<td>3</td>
</tr>
<tr>
<td>EN.601.485</td>
<td>Probabilistic Models of the Visual Cortex</td>
<td>3</td>
</tr>
</tbody>
</table>

Contact the department advising office for course additions.

**Computational Biology Focus Area - Non Upper-Level Engineering Courses**

(maximum of 3 credits from this list may count in focus area)

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>AS.110.311</td>
<td>Methods of Complex Analysis</td>
<td>4</td>
</tr>
<tr>
<td>AS.110.405</td>
<td>Analysis I</td>
<td>4</td>
</tr>
<tr>
<td>AS.110.421</td>
<td>Dynamical Systems</td>
<td>4</td>
</tr>
<tr>
<td>AS.110.443</td>
<td>Fourier Analysis</td>
<td>4</td>
</tr>
<tr>
<td>EN.580.112</td>
<td>BME Design Group</td>
<td>3</td>
</tr>
<tr>
<td>EN.580.211</td>
<td>BME Design Group</td>
<td>3</td>
</tr>
<tr>
<td>EN.580.212</td>
<td>BME Design Group</td>
<td>3</td>
</tr>
<tr>
<td>EN.580.311</td>
<td>BME Design Group</td>
<td>3</td>
</tr>
<tr>
<td>EN.580.312</td>
<td>BME Design Group</td>
<td>3</td>
</tr>
<tr>
<td>EN.580.411</td>
<td>BME Design Group</td>
<td>3</td>
</tr>
<tr>
<td>EN.580.412</td>
<td>BME Design Group</td>
<td>3</td>
</tr>
<tr>
<td>EN.580.580</td>
<td>Senior Design Project</td>
<td>3</td>
</tr>
<tr>
<td>EN.580.581</td>
<td>Senior Design Project</td>
<td>3</td>
</tr>
<tr>
<td>EN.601.231</td>
<td>Automata &amp; Computation Theory</td>
<td>3</td>
</tr>
</tbody>
</table>

Students may use a maximum of 3 research credits as a non-upper-level engineering course.

**Imaging Focus Area - Upper-Level Engineering Courses**

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN.520.401</td>
<td>Basic Communication</td>
<td>3</td>
</tr>
<tr>
<td>EN.520.414</td>
<td>Image Processing &amp; Analysis</td>
<td>3</td>
</tr>
<tr>
<td>EN.520.415</td>
<td>Image Process &amp; Analysis II</td>
<td>3</td>
</tr>
<tr>
<td>EN.520.432</td>
<td>Medical Imaging Systems</td>
<td>3</td>
</tr>
<tr>
<td>EN.520.433</td>
<td>Medical Image Analysis</td>
<td>3</td>
</tr>
<tr>
<td>EN.520.434</td>
<td>Modern Biomedical Imaging Instrumentation and Techniques</td>
<td>3</td>
</tr>
<tr>
<td>EN.520.435</td>
<td>Digital Signal Processing</td>
<td>3</td>
</tr>
<tr>
<td>EN.520.447</td>
<td>Information Theory</td>
<td>3</td>
</tr>
<tr>
<td>EN.520.454</td>
<td>Control Systems Design</td>
<td>3</td>
</tr>
<tr>
<td>EN.520.465</td>
<td>Digital Communications I</td>
<td>3</td>
</tr>
<tr>
<td>EN.520.483</td>
<td>Bio-Photonics Laboratory</td>
<td>3</td>
</tr>
<tr>
<td>EN.520.646</td>
<td>Wavelets &amp; Filter Banks</td>
<td>3</td>
</tr>
<tr>
<td>EN.520.651</td>
<td>Random Signal Analysis</td>
<td>4</td>
</tr>
<tr>
<td>EN.520.673</td>
<td>Magnetic Resonance in Medicine</td>
<td>3</td>
</tr>
<tr>
<td>EN.520.746</td>
<td>Seminar: Medical Image Analysis</td>
<td>1</td>
</tr>
<tr>
<td>EN.530.441</td>
<td>Introduction to Biophotonics</td>
<td>3</td>
</tr>
</tbody>
</table>
EN.553.361 Introduction to Optimization 4
EN.553.362 Introduction to Optimization II 4
EN.553.391 Dynamical Systems 4
EN.553.413 Applied Statistics and Data Analysis 4
EN.553.420 Introduction to Probability 4
EN.553.426 Introduction to Stochastic Processes 4
EN.553.430 Introduction to Statistics 4
EN.553.433 Monte Carlo Methods 3
EN.553.436 Data Mining 4
EN.553.472 Graph Theory 4
EN.553.493 Mathematical Image Analysis 3
EN.553.720 Probability Theory I 4
EN.553.721 Probability Theory II 4
EN.553.730 Statistical Theory 4
EN.553.731 Statistical Theory II 3
EN.580.466 Statistical Methods in Imaging 3
EN.580.471 Principles of Design of BME Instrumentation 4
EN.580.571 Honors Instrumentation (Intersession) will count as an additional 2 credits in the focus area.
EN.580.472 Medical Imaging Systems 3
EN.580.473 Modern Biomedical Imaging Instrumentation and Techniques 3
EN.580.476 Magnetic Resonance in Medicine 3
EN.580.479 X-ray Imaging and Computed Tomography 3
EN.580.483 Nuclear Medicine Imaging 3
EN.580.491 Learning Theory 3
EN.580.493 Imaging Instrumentation 4
EN.580.573 Magnetic Resonance in Medicine 3
EN.580.673 Biomedical Photonics 3
EN.580.679 X-ray Imaging and Computed Tomography 3
EN.580.683 Nuclear Medicine Imaging 3
EN.580.684 Ultrasound Imaging: Theory and Applications 3
EN.601.226 Data Structures 4
EN.601.315 Databases 3
EN.601.455 Computer Integrated Surgery I 4
EN.601.456 Computer Integrated Surgery II 3
EN.601.457 Computer Graphics 3
EN.601.461 Computer Vision 3
EN.601.475 Machine Learning 3
Contact the department advising office for course additions.

Imaging Focus Area - Non Upper-Level Engineering Courses (maximum of 3 credits from this list may count in focus area)
AS.110.405 Analysis I 4
AS.110.443 Fourier Analysis 4
EN.520.214 Signals and Systems 4
EN.580.112 BME Design Group 3
EN.580.211 BME Design Group 3
EN.580.212 BME Design Group 3
EN.580.311 BME Design Group 3
EN.580.312 BME Design Group 3
EN.580.411 BME Design Group 3
EN.580.412 BME Design Group 3
EN.580.580 Senior Design Project 3
EN.580.581 Senior Design Project 3
Students may use a maximum of 3 research credits as a non-upper-level engineering course.

Sensors, Instrumentation, and Micro/Nanotechnology Focus Area - Upper-Level Engineering Courses
EN.510.311 Structure Of Materials 3
EN.510.313 Mechanical Properties of Materials 3
EN.510.314 Electronic Properties of Materials 3
EN.510.316 Biomaterials I 3
EN.510.403 Materials Characterization 3
EN.510.407 Biomaterials II: Host response and biomaterials applications 3
EN.510.421 Nanoparticles 3
EN.510.422 Micro and Nano Structured Materials & Devices 3
EN.510.430 Biomaterials Lab 3
EN.520.216 Introduction To VLSI 3
EN.520.315 Introduction to Information Processing of Sensory Signals 3
EN.520.345 Electrical & Computer Engineering Laboratory 3
EN.520.349 Microprocessor Lab I 3
EN.520.353 Control Systems 3
EN.520.372 Programmable Device Lab 3
EN.520.401 Basic Communication 3
EN.520.407 Introduction to the Physics of Electronic Devices 3
EN.520.424 FPGA Synthesis Lab 3
EN.520.425 FPGA Senior Projects Laboratory 3
EN.520.432 Medical Imaging Systems 3
EN.520.433 Medical Image Analysis 3
EN.520.435 Digital Signal Processing 3
EN.520.447 Information Theory 3
EN.520.448 Electronics Design Lab 3
EN.520.450 Advanced Micro-Processor Lab 3
EN.520.454 Control Systems Design 3
EN.520.465 Digital Communications I 3
EN.520.483 Bio-Photonics Laboratory 3
EN.520.491 CAD Design of Digital VLSI Systems I (Juniors/Seniors) 3
EN.520.492 Mixed-Mode VLSI Systems 3
EN.530.354 Manufacturing Engineering 3
EN.530.414 Computer-Aided Design 3
EN.530.420 Robot Sensors/Actuators 4
EN.530.421 Mechatronics 3
EN.530.446 Experimental Methods in Biomechanics 3
EN.530.646 Robot Devices, Kinematics, Dynamics, and Control 4
EN.530.672 Biosensing & BioMEMS 3
EN.540.403 Colloids and Nanoparticles 3
EN.540.440 Micro/Nanotechnology: The Science and Engineering of Small Structures 3
EN.580.434 Bioelectricity 3
EN.580.441 Cellular Engineering 3
EN.580.442 Tissue Engineering 3
EN.580.451 Cell and Tissue Engineering Lab 3
or EN.580.452 Cell and Tissue Engineering Lab
EN.580.456 Introduction to Rehabilitation Engineering 3
EN.580.457 Rehabilitation Engineering Design Lab 3
EN.580.471 Principles of Design of BME Instrumentation 4
EN.580.571 Honors Instrumentation (Intersession) will count as an additional 2 credits in the focus area.
EN.580.472 Medical Imaging Systems 3
EN.580.495 Microfabrication Lab 4
EN.580.688 Foundations of Computational Biology & Bioinformatics II 3
EN.601.455 Computer Integrated Surgery I 4
EN.601.456 Computer Integrated Surgery II 3

Contact the department advising office for course additions.

Sensors, Instrumentation, and Micro/Nanotechnology Focus Area - Non Upper-Level Engineering Courses
(maximum of 3 credits from this list may count in focus area)
EN.520.213 Circuits 4
EN.520.214 Signals and Systems 4
EN.580.112 BME Design Group 3
EN.580.211 BME Design Group 3
EN.580.212 BME Design Group 3
EN.580.311 BME Design Group 3
EN.580.312 BME Design Group 3
EN.580.411 BME Design Group 3
EN.580.412 BME Design Group 3
EN.580.580 Senior Design Project 3
EN.580.581 Senior Design Project 3

Students may use a maximum of 3 research credits as a non-upper-level engineering course.

Systems Biology Focus Area - Upper-Level Engineering Courses
EN.510.311 Structure Of Materials 3
EN.510.316 Biomaterials I 3
EN.510.407 Biomaterials II: Host response and biomaterials applications 3
EN.520.345 Electrical & Computer Engineering Laboratory 3
EN.520.353 Control Systems 3
EN.520.372 Programmable Device Lab 3
EN.520.401 Basic Communication 3
EN.520.414 Image Processing & Analysis 3
EN.520.415 Image Process & Analysis II 3
EN.520.432 Medical Imaging Systems 3
EN.520.454 Control Systems Design 3
EN.520.465 Digital Communications I 3
EN.520.636 Feedback Control in Biological Signaling Pathways 3
EN.530.327 Introduction to Fluid Mechanics 3
EN.530.343 Design and Analysis of Dynamical Systems 3
EN.530.414 Computer-Aided Design 3
EN.530.420 Robot Sensors/Actuators 4
EN.530.426 Biofluid Mechanics 3
EN.530.445 Introduction to Biomechanics 3
EN.530.446 Experimental Methods in Biomechanics 3
EN.530.448 Biosolid Mechanics 3
EN.540.303 Transport Phenomena I 3
EN.540.304 Transport Phenomena II 4
EN.540.400 Project in Design: Pharmacokinetics 3
EN.540.409 Dynamic Modeling and Control 4
EN.540.414 Computational Protein Structure Prediction and Design 3
EN.540.421 Project in Design: Pharmacodynamics 3
EN.553.361 Introduction to Optimization 4
EN.553.362 Introduction to Optimization II 4
EN.553.371 Cryptology and Coding 4
EN.553.386 Scientific Computing: Differential Equations 4
EN.553.391 Dynamical Systems 4
EN.553.400 Mathematical Modeling and Consulting 4
EN.553.420 Introduction to Probability 4
EN.553.426 Introduction to Stochastic Processes 4
EN.553.430 Introduction to Statistics 4
EN.553.450 Computational Molecular Medicine 4
EN.580.418 Principles of Pulmonary Physiology 3
EN.580.420 Build-a-Genome 4
EN.580.430 Systems Pharmacology and Personalized Medicine 3
EN.580.431 Introduction to Computational Medicine I 4
EN.580.434 Bioelectricity 3
EN.580.439 Models of the Neuron 4
EN.580.445 Networks 3
EN.580.466 Statistical Methods in Imaging 3
EN.580.448 Biomechanics of the Cell 3
EN.580.456 Introduction to Rehabilitation Engineering 3
EN.580.457 Rehabilitation Engineering Design Lab 3
EN.580.460 Theory of Cancer 3
EN.580.471 Principles of Design of BME Instrumentation 4
EN.580.571 Honors Instrumentation (Intersession) will count as an additional 2 credits in the focus area.
EN.580.472 Medical Imaging Systems 3
EN.580.473 Modern Biomedical Imaging Instrumentation and Techniques 3
EN.580.491 Learning Theory 3
EN.580.492 Build-a-Genome Mentor 4
EN.580.630 Theoretical Neuroscience 3
EN.580.688 Foundations of Computational Biology & Bioinformatics II 3
EN.580.694 Statistical Connectomics 3
EN.601.455 Computer Integrated Surgery I 4
EN.601.456 Computer Integrated Surgery II 3
EN.601.463 Algorithms for Sensor-Based Robotics 3
EN.601.465 Natural Language Processing 4

Contact the department advising office for course additions.

Systems Biology Focus Area - Non Upper-Level Engineering Courses
(maximum of 3 credits from this list may count in focus area)
AS.080.305 Neuroscience: Cellular and Systems I 3
EN.520.213 Circuits 4
EN.520.214  Signals and Systems  4
EN.520.216  Introduction To VLSI  3
EN.530.201  Statics and Mechanics of Materials  4
EN.530.215  Mechanics-Based Design  3
EN.580.112  BME Design Group  3
EN.580.211  BME Design Group  3
EN.580.212  BME Design Group  3
EN.580.311  BME Design Group  3
EN.580.312  BME Design Group  3
EN.580.411  BME Design Group  3
EN.580.412  BME Design Group  3
EN.580.580  Senior Design Project  3
EN.580.581  Senior Design Project  3

Students may use a maximum of 3 research credits as a non-upper-level engineering course.

Approved Design Courses - 6 credits

This 2-semester sequence must be taken in its entirety:
EN.510.433  Senior Design Research  3
EN.510.434  Senior Design/Research II  3

EN.580.448  Electronics Design Lab  3

EN.580.454  Control Systems Design (This 1-semester course must be augmented by taking 1 semester of 580.581 Independent Design.)  3

EN.520.498  Senior Design Project  3
EN.520.499  Senior Design Project  3

This 1-semester course is augmented by taking 1 semester of 580.581 Independent Design:
EN.530.421  Mechatronics  3

This 2-semester sequence must be taken in its entirety:
EN.540.400  Project in Design: Pharmacokinetics  3
EN.540.421  Project in Design: Pharmacodynamics  3

EN.580.311  BME Design Group  3
EN.580.312  BME Design Group  3

EN.580.411  BME Design Group  3
EN.580.412  BME Design Group  3

This 2-semester sequence must be taken in its entirety:
EN.580.437  Neuro Data Design I  4
EN.580.438  Neuro Data Design II  4

EN.580.456  Introduction to Rehabilitation Engineering  3
EN.580.457  Rehabilitation Engineering Design Lab  3

EN.580.471  Principles of Design of BME Instrumentation  4

This 1-semester course must be augmented by taking 1 semester of 520.499 Independent Design:
EN.580.495  Microfabrication Lab  4

This 2-semester sequence must be taken in its entirety:
EN.580.580  Senior Design Project  3
EN.580.581  Senior Design Project  3

This 2-semester sequence must be taken in its entirety:
EN.601.455  Computer Integrated Surgery I  4
EN.601.456  Computer Integrated Surgery II  3

**Bachelor of Arts in Biomedical Engineering**

(See also General Requirements for Departmental Majors (http://catalog.jhu.edu/undergrad-students/academic-policies/requirements-for-a-bachelors-degree))

The B.A. in biomedical engineering requires 120 credits. The courses listed below must either be taken or passed by examination for advanced credit. See the Biomedical Engineering Undergraduate Advising Manual for lists of recommended courses, acceptable course substitutions, and limitations on credits for courses with overlapping material.

**Basic Sciences (22 credits)**

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>AS.171.101</td>
<td>General Physics: Physical Science Major I</td>
<td>4</td>
</tr>
<tr>
<td>or AS.171.107</td>
<td>General Physics for Physical Sciences Majors (AL)</td>
<td>4</td>
</tr>
<tr>
<td>AS.171.102</td>
<td>General Physics: Physical Science Major II</td>
<td>4</td>
</tr>
<tr>
<td>or AS.171.108</td>
<td>General Physics for Physical Sciences Majors (AL)</td>
<td>4</td>
</tr>
<tr>
<td>AS.173.111</td>
<td>General Physics Laboratory I</td>
<td>1</td>
</tr>
<tr>
<td>AS.173.112</td>
<td>General Physics Laboratory II</td>
<td>1</td>
</tr>
<tr>
<td>AS.030.101</td>
<td>Introductory Chemistry I</td>
<td>3</td>
</tr>
<tr>
<td>AS.030.102</td>
<td>Introductory Chemistry II</td>
<td>3</td>
</tr>
<tr>
<td>AS.030.105</td>
<td>Introductory Chemistry Laboratory I</td>
<td>1</td>
</tr>
<tr>
<td>AS.030.106</td>
<td>Introductory Chemistry Laboratory II</td>
<td>1</td>
</tr>
<tr>
<td>AS.030.205</td>
<td>Introductory Organic Chemistry I</td>
<td>4</td>
</tr>
</tbody>
</table>

**Mathematics (20 credits)**

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>AS.110.108</td>
<td>Calculus I</td>
<td>8</td>
</tr>
<tr>
<td>&amp; AS.110.109</td>
<td>Calculus II (For Physical Sciences and Engineering)</td>
<td>8</td>
</tr>
<tr>
<td>AS.110.202</td>
<td>Calculus III</td>
<td>4</td>
</tr>
<tr>
<td>or AS.110.211</td>
<td>Honors Multivariable Calculus</td>
<td>4</td>
</tr>
<tr>
<td>AS.110.201</td>
<td>Linear Algebra</td>
<td>4</td>
</tr>
<tr>
<td>or AS.110.212</td>
<td>Honors Linear Algebra</td>
<td>4</td>
</tr>
<tr>
<td>AS.110.302</td>
<td>Differential Equations and Applications</td>
<td>4</td>
</tr>
</tbody>
</table>

**Humanities and Social Sciences (24 credits)**

These courses should form a coherent program, with at least 9 credits chosen from one department, including at least one 300-level course.

At least four semester of writing intensive courses.

At least two semesters of a modern foreign language.

**Biomedical Core (35 credits)**

Biomedical core consists of 35 credits

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN.580.111</td>
<td>BME Modeling and Design</td>
<td>2</td>
</tr>
<tr>
<td>EN.580.202</td>
<td>BME In The Real World</td>
<td>1</td>
</tr>
<tr>
<td>EN.580.221</td>
<td>Molecules and Cells</td>
<td>4</td>
</tr>
<tr>
<td>EN.580.222</td>
<td>Computer Integrated Surgery II</td>
<td>3</td>
</tr>
</tbody>
</table>
**Master of Science in Engineering**

The master’s degree program is designed for students who wish to pursue careers in research and development, or as a step toward Ph.D. or M.D./Ph.D. education. The program has two degree options: a course-based plan consisting of 30 credits (equivalent to 10 full courses to be completed in one year) and a thesis-based track that requires 24 credits (equivalent to 8 full courses completed in the first year), 6 credits of research, plus a thesis project which is completed in a second year.

**Admission and Financial Aid**

Students with undergraduate degrees in engineering are eligible to apply. Exceptional students with degrees in basic sciences may also apply, but would normally have to take a number of courses to overcome deficiencies in their curriculum.

Financial aid is available for qualified students to serve as teaching assistants, and partial tuition remission may be available for previous Johns Hopkins students. In addition, thesis-track students (once selected for the thesis track) may be provided with additional financial aid to facilitate the research component of their degree (each financial aid package will be negotiated on an individual basis but typically will include either (or a combination of) tuition waivers or a monthly stipend.

Applications for admission are due by the appointed deadline (usually in early January).

For more information and to apply online, go to [http://www.bme.jhu.edu/graduate/mse/apply](http://www.bme.jhu.edu/graduate/mse/apply).

**Requirements for the M.S.E. Degree**

**Course-based Degree Option**

The course-based degree option will require the completion of 30 credits (the equivalent of 10 full courses) that meet the following stipulations:

- The "core requirement of two Systems Bioengineering courses. (EN.580.721, EN.580.722 or EN.580.779)
- Five additional graduate-level courses focused in a selected biomedical engineering sub-discipline (e.g., cell and tissue engineering, computational biology, imaging, instrumentation, or systems biology) as approved by the student’s advisor.
- Three additional classes that will consist of math, science, medicine, or technology coursework related to biomedical engineering, which can also include up to 4 half courses (equivalent to 2 full courses) of the JHU Center for Leadership’s Professional Development Courses (e.g., 633.645, 663.650, 663.646, and 663.651).

**Thesis-based Degree Option**

Each student will take a minimum of 24 credits (the equivalent of 8 full courses) at the graduate-level, 6 credits of research, and complete a thesis, including one or more research/practicum courses.

Students fulfill the course requirement by taking two courses in the Systems Bioengineering (SBE) sequence (580.721, 580.722 or 580.779) and other advanced engineering, math and science courses. (JHU undergraduates will replace the SBE sequence and take two additional courses in advanced engineering, math or science.)

Thesis track students must also complete a thesis based on a research topic requiring application of quantitative or applied engineering principles to biomedical engineering.

**Master of Science in Engineering in Innovation and Design**

The Center for Bioengineering Innovation and Design (CBID), housed in the Department of Biomedical Engineering, focuses on the design aspect of Biomedical Engineering. This exciting program gives students opportunities to design, develop, build, and test devices that solve some of the most pressing problems facing clinicians today.

The mission of CBID is to:

- Improve human health by developing medical devices that solve important clinical problems
- Educate a new generation of medical device engineers and fellows
- Facilitate technology transfer and industry collaboration

In the graduate program CBID students will learn to identify clinical needs and innovate a novel solution to solve that clinical problem. Working in teams, students work closely with engineering faculty and physicians throughout the medical institution to come up with device ideas, build prototypes, research intellectual property, learn about the regulatory process, write business plans, and present their designs to fellow students, faculty, and outside advisors.

Undergraduate students in BME can also become involved in medical device design by joining an undergraduate design team which works on solving clinical problems by designing innovative devices.

Incorporated in all the BME design curriculum is a focus on technology commercialization. All students, graduate and undergraduate, will interact with clinical and corporate sponsors and have experiences that promote the development of leadership, communications, and marketing skills, thus helping to ensure our graduates’ professional success.

The CBID M.S.E. is a one-year program lasting from May through the following May. Please see our website for more information on our programs: [http://cbid.bme.jhu.edu](http://cbid.bme.jhu.edu).

Information can also be found here: [http://www.bme.jhu.edu/graduate/masters-design/](http://www.bme.jhu.edu/graduate/masters-design/)
Ph.D. in Biomedical Engineering through the School of Medicine

Biomedical Engineering has emerged as one of the most exciting interdisciplinary research fields in modern science. Biomedical engineers apply modern approaches from the experimental life sciences in conjunction with theoretical and computational methods from the disciplines of engineering, mathematics, and computer science to the solution of biomedical problems of fundamental importance. The Biomedical Engineering Graduate Program of Johns Hopkins University is designed to train engineers to work at the cutting edge of this exciting discipline.

The cornerstone of the program is our belief in the importance of in-depth training of students in life sciences, modern engineering, mathematics, computer science, and in the conduct of original research leading to the doctoral dissertation. In-depth training in life sciences is achieved in one of two ways. Typically, incoming Ph.D. students enroll in the first year basic sciences curriculum of the Johns Hopkins University School of Medicine. That is, they learn human biology with the medical students. This is a unique and intensive curriculum covering a broad range of topics including molecules and cells, human anatomy, immunology, physiology, and neuroscience. Students choosing this option typically devote their entire first academic year to these courses. This curriculum is an excellent way to build a broad and solid foundation in the life sciences. Alternatively, students may elect alternative life sciences curricula. These curricula have been carefully designed to provide training in areas of the life sciences that are appropriate to each of the program’s research areas. This option is of particular value to students who enter the program having a strong background in the life sciences. In-depth training in engineering, mathematics, and computer science is achieved through elective courses that are taken in the second year.

All students are admitted with full financial support. This covers tuition and provides a modest stipend for the duration of their Ph.D. Because the students are fully funded, they can choose to perform their dissertation in essentially any laboratory in the University (subject to the approval of the Program directors). A special program with the National Heart, Lung, and Blood Institute of the National Institute of Health (NIH) allows students to also choose from research laboratories at the NIH.

Students typically do research rotations during the summer before start of the first academic semester, during the first year (typically as they are taking medical school courses), and during the following summer year. They are expected to choose a research laboratory before the start of the second academic year.

Emphasis is placed on original research leading to the doctoral dissertation. The research is usually experimental in nature, and students are expected to learn biological experimentation techniques. Nevertheless, experiment or theory can be emphasized in the research as desired by the student.

Requirements for Admission

The School of Medicine program accepts applications for the Ph.D. program until December 1 of each year. We typically recruit students in five areas: Computational Biology, Imaging, Tissue Engineering, Neural engineering, and Molecular, Neural, and Cardiac physiology (MNCP). The program is unique in that it offers the BME student the strengths of one of the best medical schools in the world. If you wish to combine engineering with cutting edge research in medicine, this may be the program for you.

In their first year, our students have the option of taking many of the same courses as the medical students, including human anatomy, molecules and cells, and genes to society. In their second year, our students take advanced engineering courses. Therefore, students that apply to our program need to not only have a strong background in engineering and mathematics, but also sufficient background in chemistry (including organic chemistry) and biology (at least two introductory courses).

The admission process is by committee. The applicant should specify which area they are interested in and write about the kind of research they are considering. The faculty in each area vote and rank the applicants. The final pool of applicants is ranked and voted on by the entire faculty.

About one third of our incoming students are international students. A short list of these students is formed by committee and the top candidates are interviewed by phone. Like all admitted students, international students receive full financial aid as well as a monthly stipend. They too have the freedom to choose from any lab.

Applications should be complete when submitted. In order to be considered a complete application we must have:

- A completed online application form.
- Official transcripts from each college or university attended—Sealed, official transcripts or certified records of all university (undergraduate and graduate) study must be submitted. If you have attended more than one institution, transcripts from each must be included with your application.
- Official Graduate Record Examination—GRE/MCAT scores will be acceptable and can be arranged through the Office of Graduate Affairs (address provided below). The GRE code for applying to graduate programs at the Johns Hopkins School of Medicine is 5316.
  - The BME Ph.D. program does not rely heavily on the GRE exam in making admissions or financial aid decisions. Research experience, course grades, and recommendations carry more weight. However, because the GRE score is part of the application and does affect admissions decisions in some cases, foreign applicants who took the GRE in its electronic form, in a country where the electronic test is no longer offered, are advised to retake the exam in its paper form. Applications will be considered regardless of which form of the exam was taken.
- Three letters of recommendation—These letters should come from faculty members who are acquainted with you and your academic work. These letters should be sealed and comment on your aptitude and promise for independent research.
- Personal Statement—a typewritten statement (one page maximum) indicating the basis of your interest in graduate study and your career objectives. Included should be a discussion of any research experience you have had.

Applicants for admission must fulfill the following course prerequisites:

- one year of college level biology (may include quantitative biology or physiology)
- one semester of organic chemistry
- differential equations

If you are interested in applying and do not have the prerequisite courses, you may want to submit your application with an explanatory note indicating you have made or will make arrangements to take
of their program. The remaining time is spent in thesis research. The program typically takes five to six years to complete.

The student must pass a preliminary oral examination which will be a Graduate Board examination. This is taken no later than the end of the second year. The student must then conduct original research, describe it in a dissertation, and pass a final oral examination that is a defense of the dissertation. There is a minimum residency requirement of two consecutive academic years.

**Integrated M.D./Ph.D. Program**

Candidates for the Ph.D. in biomedical engineering who wish to apply jointly for the M.D. degree must apply directly through the School of Medicine. Although the combined programs would normally require at least seven years to execute sequentially, the combined program can ordinarily be completed in six years, with appropriate planning. Good preparation in biology and chemistry as well as mathematics, engineering, and the physical sciences is essential. Life science graduate requirements are met by the first-year program of the School of Medicine. This program is more arduous than the Ph.D. program alone, but it may have marked advantages for students interested in clinical research and applications in hospital systems and in the delivery of health care. The catalog for the School of Medicine should be consulted for admissions requirements and procedures.

Information about applying to the combined M.D.-Ph.D. program can be found at www.hopkinsmedicine.org/mdphd/admissions (http://www.hopkinsmedicine.org/mdphd/admissions). Applications submitted for consideration of the combined degree will be reviewed by the Medical School admissions committee. If the Medical School admissions committee accepts the application, it is then passed along to the Biomedical Engineering Ph.D. Program admissions committee for review. A student applying to the combined program who wishes to be considered for the straight Ph.D. program must submit a written request to have his or her application forwarded to the Biomedical Engineering Ph.D. Program office for admission consideration if his or her application is not accepted by the Medical School admissions committee.

For current faculty and contact information go to http://www.bme.jhu.edu/people/completefacultylist.php

**Faculty**

**Chair**
Michael I. Miller
Bessie Massie Professor and Director: computational anatomy, medical imaging, image understanding.

**Professors**
Joel S. Bader
Bioinformatics, computational biology, systems biology, synthetic biology.

Kathleen E. Cullen
Multisensory integration for action and perception, neural mechanisms of motor learning, neural prosthesis and rehabilitation, computational neuroscience.

Jennifer H. Elisseeff
Jules Stein Professor: tissue engineering, biomaterials, cartilage regeneration.

Andrew P. Feinberg
Bloomberg Distinguished Professor: epigenetics of development and disease; stochasticity in development and cancer.

Taekjip Ha
Bloomberg Distinguished Professor: single molecular engineering and biophysics, DNA/RNA nanotechnology, cell mechanics, super-resolution microscopy.

Xingde Li
Endomicroscopy technologies, nanobiophotonics and molecular imaging, early detection (cancer, cardiovascular diseases, wound healing).

Aleksander S. Popel
Physiological flows and molecular transport, microcirculation, cell mechanics.

Steven L. Salzberg
Bloomberg Distinguished Professor: bioinformatics and computational biology.

Reza Shadmehr
Director of the Biomedical Engineering PhD Program: human motor control and learning in health and disease, functional imaging of the brain, human neurophysiology, computational and theoretical neuroscience.

Jeffrey H. Siewerdsen
Medical imaging, image-guidance, flat-panel imagers, cone-beam CT, volume imaging, MRI, image science, imaging performance, radiation therapy.

Nitish V. Thakor
Medical instrumentation, medical micro and nanotechnologies, neurological instrumentation, signal processing, and neural prosthetics.

Natalia Trayanova
Murray B. Sachs Professor: computational cardiac electrophysiology and electro-mechanics, mechanisms of arrhythmogenesis and cardiac anti-arrhythmia therapies, cardiac dyssynchrony and resynchronization, development of cardiac models from imaging modalities.

Leslie Tung
Co-Director of the Undergraduate Program in Biomedical Engineering: functional electro-physiology of cultured cardiac cell networks, cardiac arrhythmias, analysis of multicellular structure, stem cell-derived cardiac cells.

Rene Vidal
Computer vision (camera sensor networks, recognition of human activities, dynamic scene analysis, structure from motion), biomedical imaging (processing of high angular resolution diffusion imaging, registration and segmentation of diffusion MRI, segmentation and fiber tracking of cardiac MRI, interactive medical image segmentation), machine learning (generalized principal component analysis, manifold learning and clustering, classification of dynamical systems), signal processing (consensus on manifolds, distributed optimization, compressive sensing).

Xiaojin Wang
Neurophysiology of the auditory cortex, neural mechanisms of speech perception and learning, computational neuroscience.

Raimond L. Winslow
Raj and Neera Singh Professor of Biomedical Engineering: computational cell biology, systems biology, cardiac electrophysiology.

Associate Professors
Michael A. Beer
Genomics and computational molecular biology.

Harry R. Goldberg
Assistant Dean of the School of Medicine: virtual learning systems, student learning, web-based instruction.

Warren L. Grayson
Tissue engineering, stem cells, bioreactors, biomaterials, orthopaedics.

Jordan J. Green
Cellular engineering, nanobiotechnology, biomaterials, controlled drug delivery and gene delivery.

Rachel Karchin
Computational molecular biology, bioinformatics, genetic variation.

Scot C. Kuo
Cell motility and mechanics, nanoscale biophysics, laser-based bioinstrumentation, advanced multiphoton and confocal microscopy.

Feilim Mac Gabhann
Computational modeling of growth factor-receptor networks, personalized medicine, individualized medicine, experimental studies of interindividual variation, therapeutic cardiovascular remodeling, novel methods for data visualization and automated image analysis, computational models of virus-host interactions.

Sridevi Sarma
Closed-loop deep brain stimulation, control theory, computational neuroscience and large-scale optimization.

Kevin J. Yarema
Director of the Biomedical Engineering MSE Program: metabolic glycoengineering, glycobiology, systems biology of glycosylation, carbohydrate-based cancer drug design and delivery, cellular responses to static magnetic fields.

Kechen Zhang
Theoretical neuroscience, computational neuroscience, neural computation.

Assistant Professors
Angelo Homayoun All
Spinal cord injury, stem cells, electrophysiology, imaging.

Patrick Cahan
Computational biology, stem cell biology, and single cell genomics.

Vikram Chib
Decision-making, motivation, movement, neuroscience, robotics, neuroeconomics.

Nicholas J. Durr
Biomedical Engineering

Medical imaging, biomedical optics, endoscopy, ocular diagnostics, biomicroscopy, and medical device design.

Daniel Herzka
Cardiac magnetic resonance imaging, self-navigation, open-ended imaging, fast imaging, high resolution imaging, applications of MRI in cardiac electrophysiology, kinematic imaging, and fetal imaging.

Jamie Spangler
Structural and molecular immunology, protein engineering, therapeutic antibody discovery and design, targeted drug development.

J. Webster Stayman
Imaging physics, 3D image reconstruction, novel imaging systems, image-guided interventions and diagnostic imaging.

Winston Timp
Epigenetics, single cell analysis, single molecule biophysics, nanotechnology, systems biology, computational biology/bioinformatics.

Joshua T. Vogelstein
Big data science, connectomics, statistical neuroscience.

Youseph Yazdi
Medical instrumentation, medical device design, translation and commercialization of medical devices, biophotonics, optical spectroscopy.

Instructor
Wojciech B. Zbijewski
System modeling for optimization of X-ray CT imaging chain, integration in novel reconstruction algorithms.

Professors Emeriti
Richard J. Johns
University Distinguished Service Professor: Industrial liaison.

Murray B. Sachs
University Distinguished Service Professor: Auditory neurophysiology and psychophysics.

Lawrence P. Schramm
Spinal cord injury and regeneration, neural regulation of the circulation.

Artin A. Shoukas
Systems analysis of circulatory systems, systems physiology.

Eric D. Young
Auditory neurophysiology, neural modeling, sensory processes.

Adjunct Professor
Elliot R. McVeigh
Imaging.

Adjunct Associate Professor
Xiaofeng Jia
Novel application of neuro-electrophysiology for detection and restoration of peripheral nerve and spinal cord injury, basic and clinical investigations in neurological injuries and therapeutic hyperthermia of brain and spinal cord after asphyxial cardiac arrest.

Adjunct Assistant Professors
Ivy Dick
Ca2+ signaling mechanisms in neuronal and cardiac systems, Ca2+ channels, electrophysiology, channelopathies.

Thomas W. Gilbert
Extracellular matrix scaffold materials for development of regenerative medicine.

J. Jeremy Rice
Muscle physiology, motor proteins, calcium handling, electrophysiology, simulation, systems biology, neuroscience.

Research Professor
Andre Levchenko
Intracellular signal transduction, cell engineering, cancer research.

Alexander A. Spector
Biosolid mechanics, cell mechanics and biophysics, membrane mechanics, mechanotransduction, molecular motors, mathematical and computational modeling.

Associate Research Professor
Patrick Barta
Neuroimaging, psychiatry, psychiatry and behavioral sciences.

J. Tilak Ratnanather
Computational anatomy, biomedical imaging, numerical analysis, mathematical biology of the cochlea.

Assistant Research Professor
Soumyadipta Acharya
Director of the Master’s degree program in Bioengineering Innovation and Design: Biomedical instrumentation, medical device innovation, neuroprosthetics, brain machine interfaces, computational neuroscience.

Siamak Ardekani
Image-based (multi-detector CT and MRI) shape and motion analysis of cardiac disease using mathematical models, analysis of brain development and aging process using diffusion MRI and deformation based morphometry.

Patrick M. Boyle
Computational simulations of cardiac electrophysiology to explore mechanisms of arrhythmia initiation, perpetuation, and termination; personalized treatment plans for cardiac radiofrequency ablation procedures; novel anti-arrhythmia approaches based on cardiac optogenetics.

David Masica
Novel computational methods to predict the impact of (epi)genetic alterations on human disease and drug response.

Research Associate
Matthew Jacobson
Tomographic image reconstruction, parameter estimation in medical imaging, cone beam CT, image guidance, geometric computer vision.

Kideok Jin
Drug resistant cancer, metastasis, angiogenesis, drug discovery.

Manu Ben Johny
Drug resistant cancer, metastasis, angiogenesis, drug discovery.

Ramsey Kraya
Michael Scott Osmanski
Auditory neuroscience, perception and cortical representation of complex sounds, acoustic communication, comparative and evolutionary biology of hearing.
Niranjan Pandey
Gaurav K. Thawait
Karen I. Zeller
Synthetic biology.

Senior Lecturers
Eileen Haase
Co-Director of the Undergraduate Program in Biomedical Engineering: Freshmen Modeling and Design, System Bioengineering Laboratory I and II, Cell and Tissue Engineering Laboratory, Molecules and Cells, BME Teaching Practicum.

Lecturers
Elizabeth A. Logsdon
Engineering design education, online learning.

Amir Manbachi
Medical imaging, neurosurgery, spine interventions, and medical device design.

Joint, Secondary, Part-Time, and Visiting Appointments
Mohamad E. Alfal
Associate Professor (Urology): laparoscopic and robotic surgery.

William S. Anderson
Associate Professor (Neurological Surgery): cerebrospinal fluid disorders and movement disorders.

Muyinatu A. Lediju Bell
Assistant Professor (Electrical and Computer Engineering): ultrasonic imaging, photoacoustic imaging, coherence-based beamforming, image formation, image quality, light delivery systems, medical robotics, image-guided surgery, image-guided interventions, speckle tracking, technology development, medical device design, clinical translation.

Ronald D. Berger
Professor (Cardiology): mechanisms of sudden cardiac death, new modalities of ablation therapy, device development, signal processing.

Dan E. Berkowitz
Professor (Anesthesiology and Critical Care Medicine): molecular mechanisms of cardiovascular deconditioning in rodent models of microgravity, vasoregulatory dysfunction associated with obesity, diabetes, the role of leptin in vasoregulatory changes.

Paul A. Bottomley
Professor (Radiology): magnetic resonance imaging and spectroscopy, medical imaging.

Henry Brem
Professor (Neurosurgery): clinical treatments for brain tumour, anti-angiogenesis therapies, computer navigation systems used during surgery, brain tumor vaccines.

John A. Carrino
Associate Professor (Radiology and Radiological Science): spine imaging novel MRI techniques, health services research informatics.

Jiande Chen
Professor (Gastroenterology): electrogastrography.

Charles C. Della Santina
Associate Professor (Otolaryngology-Head and Neck Surgery): electrical stimulation of the inner ear for restoring balance function, neurophysiology, vestibular function testing.

Andrew S. Douglas
Vice Dean for Faculty for the Whiting School of Engineering, Professor (Mechanical Engineering): nonlinear solid mechanics, soft tissue mechanics, mechanics of active materials.

Andrew Ewald
Associate Professor (Cell Biology and Oncology): cellular mechanisms and molecular regulation of epithelial morphogenesis in development and cancer.

Gene Fridman
Assistant Professor (Otolaryngology-Head and Neck Surgery): novel methods and devices for neural interfacing.

Paul A. Fuchs
Professor (Otolaryngology-Head and Neck Surgery): biophysics and sensory physiology of sensory hair cells and neurons on the inner ear.

Donald Geman
Professor (Applied Mathematics and Statistics): statistical learning, visual recognition, computational genomics.

Henry R. Halperin
Professor (Cardiology): cardiovascular medicine, MR compatible devices.

Justin Hanes
Professor (Ophthalmology): drug and gene delivery, biomaterials synthesis, particle transport through biological barriers.

Kalina Hristova
Professor (Materials Science and Engineering): biomolecular materials, biomembranes, biosensor development, signal transduction across biological membranes.

Chao-Wei Hwang
Assistant Professor (Cardiology): optimization of PCI and stent-based drug delivery using computational fluid dynamics, cell-based therapy for the heart and peripheral vasculature, active sensing drug delivery systems.

Pablo A. Iglesias
Professor (Electrical and Computer Engineering): computational biology, models of cellular signal transduction, directed cell motility, cell division, control systems.

Takanari Inoue
Associate Professor (Cell Biology): directed cell migration, tumor metastasis, primary cilia, synthetic chemical biology, technology development.

David A. Kass
Professor (Cardiology): molecular pathophysiology of heart failure and hypertrophy, pathobiology of cardiac dyssynchrony and resynchronization, cardiac stress regulation by phosphodiesterase 5, nitric oxide synthase uncoupling, structure-function of sarcomeric proteins to cardiac mechanics, heart failure with preserved ejection fraction.

A. Jay Khanna
Professor (Orthopaedic Surgery): spine surgery, minimally invasive, musculoskeletal imaging, image guidance for surgery, MRI, biomechanics, clinical outcomes.
Konstantinos Konstantopoulos  
Professor (Chemical and Biomolecular Engineering): cell adhesion and microfluidics, nanoscale mechanics, receptor biochemistry, quantitative modeling and functional genomics.

Albert C. Lardo  
Associate Professor (Cardiology): cardiovascular MRI, cardiovascular CT, image guided therapy.

Rong Li  
Bloomberg Distinguished Professor (Cell Biology): cellular dynamics in space, time, and adaptation.

Hanzhang Lu  
Associate Professor (Radiology): development of novel MRI technologies and applications for the measurement of vital physiological and biophysical parameters.

Hai-Quan Mao  
Professor (Materials Science and Engineering): nanomaterials, electrospinning, nanofibers, biomimetic matrix, stem cell expansion and differentiation, nerve regeneration, micellar nanoparticle, therapeutic delivery, biodegradable polymers.

Wayne Mitzner  
Professor (Environmental Health Sciences, Program in Respiratory Biology and Lung Disease): modeling lung function, lung structure-function interactions, mechanical aspects of lung disease.

Hien Nguyen  
Assistant Professor (Surgery): clinical outcomes in hernia surgery, critical care medicine, bariatric surgery and metabolic syndrome.

Arvind P. Pathak  
Associate Professor (Radiology): functional and molecular imaging, systems biology, tumor microenvironment, multiscale imaging, computational and visualization tools.

Jerry L. Prince  
Professor (Electrical and Computer Engineering): image processing and computer vision with application to medical imaging.

Lewis H. Romer  
Professor (Anesthesiology and Critical Care Medicine, Cell Biology, and Pediatrics, and the Center for Cell Dynamics): tissue engineering the micro-vasculature, extracellular matrix as an instructive environment, biophysics and biochemistry of matrix assembly, interactions between tyrosine kinases and Rho family GTPases in cell matrix adhesion, mechanochemical coupling in cell-matrix adhesion signaling, harnessing stem and progenitor cells for microvascular restitution.

Lakshmi Santhanam  
Assistant Professor (Anesthesiology and Critical Care Medicine): molecular mechanisms of vascular stiffness.

Akira Sawa  
Professor (Psychiatry and Behavioral Sciences): pathogenesis of mental illnesses, especially schizophrenia and mood disorders, at the molecular level.

Lew Schon  
Associate Professor (Orthopaedic Surgery): surgical delivery systems for stem cells and bioactive molecules.

Joseph M. Smith  
Adjunct Associate Professor (Biomedical Engineering): health care innovations and technologies.

Benjamin M.W. Tsui  
Professor (Radiology): molecular imaging including SPECT, PET and CT, anatomical and physiological models of humans and small animals, simulation of imaging systems and processes, quantitative image reconstruction methods, image quality assessment.

Jeff Tza-Huei Wang  
Professor (Mechanical Engineering): bioMEMS and microfluidics, single molecule manipulation and detection, nano/micro scale fabrication, conformational dynamics of biomolecules.

Clifford R. Weiss  
Assistant Professor (Radiology and Surgery): Clinical Director of the Johns Hopkins Center for Bioengineering, Innovation and Design (CBID).

Thomas B. Woolf  
Professor (Physiology): molecular dynamics calculations, membrane biophysics, computational neurosciences.

Laurent Younes  
Professor (Applied Mathematics and Statistics): statistical properties of Markov random fields, image analysis, deformation analysis-shape recognition.

Elias Zerhouni  
Professor (Radiology): imaging.

For current course information and registration go to https://sis.jhu.edu/classes/

**Courses**

**EN.580.105. Intellectual Property Primer for Scientists and Engineers: Patents, Copyrights, and Trademarks. 1.0 Credit.**

The course will outline the basics of intellectual property laws with an emphasis on practical aspects of protection of IP for scientists and engineers. Most of the course will cover the basics of patent law, but introductions will also be given to trademarks and copyrights. Specific problems in the areas of biotechnology, computer science and the Internet will also be highlighted. It is hoped that the attendees will obtain a basic understanding of how intellectual property is protected. No prior legal background is required.

Instructor(s): J. Szipl

Area: Social and Behavioral Sciences.
EN.580.106. Discover Hopkins: Nanoparticles for Drug Delivery Applications. 1.0 Credit.
Humans have used medication to treat diseases for many centuries; however, with the ever growing pharmaceuticals industry and stronger, more effective agents being designed, it has become clear that getting these drugs to their target cells only is a significant issue. Possibly the most striking example is intravenously (IV) administered chemotherapy agents. Patients receiving IV chemotherapy experience severe side-effects throughout their entire body such as hair loss, fatigue, nausea and general pain. This clearly illustrates the need for delivering drugs locally or targeting them to reach only the desired tissues, and this is where the field of nanoparticle drug delivery comes into play. Drug delivery involves encapsulating drugs in a delivery vehicle that can help sustain the release at therapeutic levels over an increased period of time and deliver it to the desired site. This course will focus on current developments as well as the methods used in the field of nanoparticle.
Instructor(s): C. Bishop; K. Maisel
Area: Engineering, Natural Sciences.

EN.580.111. BME Modeling and Design. 2.0 Credits.
Working in teams with upperclassmen this course (1) introduces biomedical engineering freshmen to an orderly method for analyzing and modeling biological systems and (2) introduces engineering principles to solve design problems that are biological, physiological, and/or medical. Freshmen are expected to use the informational content being taught in calculus, physics and chemistry and to apply this knowledge to the solution of practical problems encountered in biomedical engineering.
BME Freshmen only.
Prerequisites: Students must have completed Lab Safety training prior to registering for this class.
Instructor(s): E. Haase; E. Logsdon; P. Boyle
Area: Engineering, Natural Sciences.

EN.580.112. BME Design Group. 3.0 Credits.
A two-semester course sequence where freshmen work with groups of BME upperclassmen mentors, and learn to use engineering principles to solve design problems that are biological, physiological, and/or medical. Freshmen are expected to use the informational content being taught in calculus, physics, and chemistry and apply this knowledge to the solution of practical problems encountered in biomedical engineering.
Instructor(s): E. Logsdon; N. Durr; R. Allen
Area: Engineering, Natural Sciences.

This course is an introduction to scientific programming and computing designed for first-year students. The aim is to develop core computer skills required to succeed in research. Programming projects are drawn from current biomedical applications within BME. Emphasis is on algorithm development, large scale data analysis, and effective visualization of results, using MATLAB, Python, and R. Prior programming experience is not required.
Instructor(s): W. Timp
Area: Engineering.

EN.580.202. Bme In The Real World. 1.0 Credit.
Open only to engineering students; A series of weekly lectures to inform students about careers in biomedical engineering and to discuss technological, social, ethical, legal, and economic issues relevant to the profession. Topics include academic careers in biomedical engineering; biomedical engineering in industry (large corporations to sole entrepreneurship); health care delivery; ethical issues; legal issues (patenting, licensing, product liability); standards and government regulations; and economic issues in biomedical engineering industry (start-up companies, global businesses).
Instructor(s): A. Popel.

EN.580.211. BME Design Group. 3.0 Credits.
Sophomore-level version of EN.580.311-312 or Perm. Req’d
Instructor(s): A. Manbachi; E. Logsdon; N. Durr
Area: Engineering, Natural Sciences.

EN.580.212. BME Design Group. 3.0 Credits.
Sophomore-level version of EN.580.111-112. Permission of course directors required.
Instructor(s): E. Logsdon; N. Durr; R. Allen
Area: Engineering, Natural Sciences.

EN.580.220. he Science of Medicine: Thinking Critically. 3.0 Credits.
This course investigates some of the most pressing issues in biomedical science with direction from leading clinicians, scientists, policy experts, and industry professionals. The underlying science and ethical implications for topics such as “Rogue Clinics and Designer Babies: How can I decide the genotype of my offspring – and should I?,” “Mosquito-borne Diseases: Fighting an enemy that outweighs us 15,000 to one with genetics,” and “HIV: Pushing for a cure versus settling for a treatment: What makes healthcare sufficient” are explored. The class is taught in a flipped method: students will be expected to listen to presentations at home so that class time can be devoted to problem solving activities, experimental design, debates, and discussion. The goal of this course is to teach students how to think critically and to expose students to the great unknowns that remain in science today.
Instructor(s): C. Hanlon; E. Haase; H. Goldberg
Area: Natural Sciences.

EN.580.221. Molecules and Cells. 4.0 Credits.
An introduction to modern molecular and cellular biology in the context of potential biomedical engineering applications. Topics covered: reactions between molecules, including receptor-ligand and antigen-antibody specificity, protein structure, enzyme catalysis, genetic information, protein processing and secretion, cell physiology and cell functions. Along with detailed study of molecular pathways and cellular behavior, we will discuss the quantitative study of molecular and cellular biology. Recommended Course Background: AS.030.101 and AS.030.104
Instructor(s): E. Haase; F. Macgabhann; K. Yarema
Area: Natural Sciences.

EN.580.222. Systems and Controls. 4.0 Credits.
An introduction to linear systems: analysis, stability and control. Topics include first and second order systems, linear time invariant discrete and continuous systems, convolution, Fourier series, Fourier transforms, Laplace transforms, stability of linear systems, input output and state space representation of linear systems, stability, observability, controlability, and PID controller design. Recommended Course Background: AS.171.102 and AS.110.201, AS.110.302 or EN.553.291
Instructor(s): M. Miller; S. Sarma
Area: Engineering.
EN.580.223. Models and Simulations. 4.0 Credits.
This course introduces students to modeling and analysis of biological systems. The first portion of the course focuses on linear systems. Topics include harmonic oscillators, pharmacokinetics, reaction-diffusion equation, heat transfer, and fluid flow. The second half of the course focuses on non-linear systems. Topics include iterated maps, bifurcations, chaos, stability of autonomous systems, the Hodgkin-Huxley model, bistability, limit cycles, and the Poincare-Bendixson theorem. The course also introduces students to the Matlab programming language, which allows them to implement the models discussed in class. Recommended Course Background: AS.110.201, AS.110.302, or EN.553.291
Instructor(s): A. Popel; M. Beer
Area: Engineering.

EN.580.238. Freshman/Sophomore Neuro Data Design. 3.0 Credits.
This course is intended for freshmen or sophomores who want to join an existing team in the spring. See description for EN.580.437-438. Students will work in small teams on the next phase of a project for the targeted brain science community. The spring semester will focus on developing the tool, getting regular feedback, and iterating, using the agile/lean development process. Recommended background: numerical programming.
Instructor(s): J. Vogelstein
Area: Engineering.

EN.580.256. Rehabilitation Engineering Seminar. 3.0 Credits.
The primary objective of this course is to introduce students to the challenges of engineering solutions for persons functioning with disabilities. In order to achieve this goal, other objectives include: gaining a basic appreciation of the modalities used to treat impairments, the opportunities for application of engineering to improve treatment delivery, understanding the science and engineering applied to helping persons with disabilities function in the everyday world and an basic knowledge of the legal, ethical issues and employment opportunities in rehabilitation engineering. Students must attend at least 70% of lectures to receive a satisfactory (S) grade.
Instructor(s): S. Paul.

EN.580.302. Careers in Biomedical Engineering. 1.0 Credit.
See description for EN.580.202. This course is designed for upperclassmen that wish to meet with weekly speakers to discuss careers issues. Junior/Senior Engineers only.
Instructor(s): A. Popel.

EN.580.311. BME Design Group. 3.0 Credits.
A two-semester course sequence where juniors and seniors work with a team leader and a group of BME freshmen and sophomores, to solve open-ended problems in biomedical engineering. Upperclassmen are expected to apply their general knowledge and experience, and their knowledge in their concentration area, to teach lower classmen and to generate the solution to practical problems encountered in biomedical engineering. Perm. Req’d.
Instructor(s): A. Manbachi; E. Logsdon; N. Durr; R. Allen
Area: Engineering, Natural Sciences.

EN.580.312. BME Design Group. 3.0 Credits.
A two semester course sequence where juniors and seniors work with a team leader and a group of BME freshmen and sophomores, to solve open-ended problems in biomedical engineering. Upperclassmen are expected to apply their general knowledge and experience, and their knowledge in their concentration area, to teach lower classmen and to generate the solution to practical problems encountered in biomedical engineering.
Instructor(s): E. Logsdon; N. Durr; R. Allen
Area: Engineering, Natural Sciences.

EN.580.321. Statistical Mechanics and Thermodynamics. 4.0 Credits.
Basic principles of statistical physics and thermodynamics with application to biological systems. Topics include fundamental principles of thermodynamics, chemical equilibrium and thermodynamics of reactions in solutions, and elementary statistical mechanics. Recommended Course Background: AS.110.108-AS.110.109, AS.030.101-AS.030.102, AS.171.101-AS.171.102; Freshman/Sophomore Chemistry and Physics
Instructor(s): M. Beer
Area: Engineering, Natural Sciences.

EN.580.407. Design Team Clinical Immersion. 1.0 Credit.
In this course design team leaders will undergo training in clinical need identification through clinical immersion in the Johns Hopkins Hospital System. Leaders will learn observation techniques, survey methods, mind-mapping and root-cause analysis. Dates: Tues 1/17- Friday 1/20, Monday 1/23 - Friday 1/27 The schedule for this class will change with clinical practice but will generally fall within the hours of 6am - 6pm.
Instructor(s): E. Logsdon; N. Durr.

EN.580.408. Design Team Leader Seminar. 1.0 Credit.
This course prepares undergraduate students to lead teams for the subsequent Design Teams course. This course will teach leadership skills, expose students to project options and clinical sponsors, and prepare them to plan and execute a biomedical design project. Course will meet in the Clark Hall Design Studio and the Carnegie Building (SoM) Design Studio.
Instructor(s): E. Logsdon; N. Durr.

EN.580.410. Effective Teaching and Management of Engineering Teams. 2.0 Credits.
Senior biomedical engineering students will assist the core course instructors and PhD students in managing the sections and recitations and or lab component of a course. Permission required.
Instructor(s): E. Haase.

EN.580.411. BME Design Group. 3.0 Credits.
Perm. Req’d. Senior-level version of EN.580.311-312.
Instructor(s): A. Manbachi; E. Logsdon; N. Durr; R. Allen
Area: Engineering.

EN.580.412. BME Design Group. 3.0 Credits.
Senior-level version of EN.580.311-312. Permission of course directors required
Instructor(s): E. Logsdon; N. Durr; R. Allen
Area: Engineering.

EN.580.413. Design Team, Team Leader Seminar. 1.0 Credit.
This course is for Design Team leaders actively leading a team for the academic year. This course focuses on development of leadership, communication and team management skills in the context of biodesign.
Instructor(s): A. Manbachi; E. Logsdon; N. Durr
Area: Engineering.
EN.580.414. Design Team, Team Leader Seminar. 1.0 Credit.
This course is for Design Team leaders actively leading a team for the academic year. This course focuses on development of leadership, communication and team management skills in the context of biodesign. Instructor(s): E. Logsdon; N. Durr; R. Allen
Area: Engineering.

EN.580.415. Ethics of Biomedical Engineering Innovation. 3.0 Credits.
Engineers confront problems and make decisions that hold long term social consequences for individuals, organizations, communities and the profession. For biomedical engineers, these decisions may relate to: inventions such as medical devices and pharmaceuticals; neural prosthetics and synthetic biological organisms; responsible and sustainable design; availability of biotechnology in the developing world. Using a combination of cases, fieldwork and readings, we examine the ethical issues, standards, theory and consequences of recent and emerging engineering interventions as a way to understand the profession and to form a basis for future decisions. In addition students will learn and practice multiple forms of communication, including oral, visual and written rhetoric. A particular focus will be communication targeted to different stakeholders including other professionals and the public. Students will apply good communication principle to the discussion of biomedical engineering ethics, develop their own ethical case studies and participate in group projects to aid ethical decision-making, and to improve communication of complex biomedical ethical issues to others.
Instructor(s): F. Macgabhann
Area: Social and Behavioral Sciences
Writing Intensive.

EN.580.416. BME Advanced Teaching Practicum. 3.0 Credits.
Senior biomedical engineering students will assist the core course instructors in managing the sections, recitations, or lab component of a course. Permission required.
Instructor(s): E. Haase

EN.580.418. Principles of Pulmonary Physiology. 3.0 Credits.
This course will provide students with an introduction to concepts in the structure and function of the respiratory system. Topics to be covered will include basic anatomy, lung mechanics, gas exchange, tests of pulmonary function and cardiopulmonary exercise, and the effects of disease on aspects of the respiratory system. Class sessions will mix both lecture and hands-on measurement, and will include discussion of instrumentation used in pulmonary measurements and a field trip to a clinical physiology laboratory at JHH. Recommended background: Chemistry, Physics, and Calculus II, and EN.580.222 Systems and Controls or equivalent.
Instructor(s): D. Shade
Area: Engineering, Natural Sciences.

EN.580.420. Build-a-Genome. 4.0 Credits.
Must understand fundamentals of DNA structure, DNA electrophoresis and analysis, Polymerase Chain Reaction (PCR) and must be either a) Experienced with molecular biology lab work or b) Adept at programming with a biological twist. In this combination lecture/laboratory "Synthetic Biology" course students will learn how to make DNA building blocks used in an int'l. project to build the world’s first synthetic eukaryotic genome, Saccharomyces cerevisiae v. 2.0. Please study the wiki www.syntheticyeast.org for more details about the project. Following a biotechnology boot-camp, students will have 24/7 access to computational and wet-lab resources and will be expected to spend 15-20 hours per week on this course. Advanced students will be expected to contribute to the computational and biotech infrastructure. Successful completion of this course provides 3 credit hours toward the supervised research requirement for Molecular and Cellular Biology majors, or 2 credit hours toward the upper level elective requirement for Biology or Molecular and Cellular Biology majors.
Prerequisites: Students must have completed Lab Safety training prior to registering for this class.
Instructor(s): J. Bader; K. Zeller
Area: Engineering, Natural Sciences.

EN.580.421. Systems Bioengineering I. 4.0 Credits.
A quantitative, model-oriented investigation of the cardiovascular system. Topics are organized in three segments. (1) Molecular/cellular physiology, including electrical signaling and muscle contraction. (2) Systems cardiovascular physiology, emphasizing circuit-diagram analysis of hemodynamics. (3) Cardio-vascular horizons and challenges for biomedical engineers, including heart failure and its investigation/treatment by computer simulation, by gene-array analysis, by stem-cell technology, and by mechanical devices (left-ventricular assist and total-heart replacement). Recommended Course Background: EN.580.221 and EN.580.222
Instructor(s): N. Trayanova
Area: Engineering, Natural Sciences.

EN.580.422. Systems Bioengineering II. 4.0 Credits.
A quantitative, model-oriented approach to the study of the nervous system. Topics include functional anatomy of the central and autonomic nervous systems, neurons and networks, learning and memory, structure and function of the auditory and visual systems, motor systems, and neuro-engineering. Recommended Course Background: EN.580.221, EN.580.222, EN.580.223, AS.110.302, EN.580.421; Corequisite: EN.580.424
Instructor(s): E. Haase; X. Wang
Area: Engineering, Natural Sciences.

EN.580.423. Systems Bioengineering Lab I. 2.0 Credits.
A two-semester laboratory course in which various physiological preparations are used as examples of problems of applying technology in biological systems. The emphasis in this course is on the design of experimental measurements and on physical models of biological systems. Priority to Junior BME majors. Recommended Corequisite: EN.580.421.
Prerequisites: Students must have completed Lab Safety training prior to registering for this class.
Instructor(s): E. Haase
Area: Natural Sciences.
EN.580.424. Systems Bioengineering Lab. 2.0 Credits.
A laboratory course in which various physiological preparations are used as examples of problems of applying technology in biological systems. The emphasis in this course is on the design of experimental measurements and on physical models of biological systems. Recommended Corequisite: EN.580.422
Prerequisites: Students must have completed Lab Safety training prior to registering for this class.
Instructor(s): E. Haase.

EN.580.425. Ion Channels in Excitable Membranes. 3.0 Credits.
 Ion channels are key signaling molecules that support electrical communication throughout the body. As such, these channels are a central focus of biomedical engineering as it relates to neuroscience, computational biology, biophysics, and drug discovery. The course introduces the engineering and molecular strategies used to understand the function of ionic channels. The course also surveys key papers that paint the current picture of how ion channels open and conduct ions. Biological implications of these properties are emphasized throughout. Finally, the course introduces how optical and electrophysiological methods now promise to revolutionize understanding of ionic channels. This course can be seen as a valuable partner of Models of the Neuron (EN.580.439). Recommended Course Background: EN.580.421 and EN.580.422 or equivalent, AS.110.201, AS.110.302
Area: Engineering, Natural Sciences.

EN.580.429. Systems Bioengineering III. 4.0 Credits.
Computational and theoretical systems biology at the cellular and molecular level. Topics include organizational patterns of biological networks; analysis of metabolic networks, gene regulatory networks, and signal transduction networks; inference of pathway structure; and behavior of cellular and molecular circuits. Recommended Course Background: EN.580.221 and EN.580.222 or Permission Required.
Instructor(s): J. Bader
Area: Engineering, Natural Sciences.

EN.580.430. Systems Pharmacology and Personalized Medicine. 3.0 Credits.
We have moved beyond the 'one-size-fits-all' era of medicine. Individuals are different, their diseases are different, and their responses to drugs are different too. This variability is not just from person to person; heterogeneity is observed even between tumors within the same person, and between sites within the same tumor. These levels of variability among the human population must be accounted for to improve patient outcomes and the efficiency of clinical trials. Some of the ways in which this is being explored include: drugs are being developed hand-in-hand with the tests needed to determine whether or not they will be effective; tumor fragments excised from patients are being cultured in the lab for high-throughput testing of drugs and drug combinations; data-rich assays such as genomics and proteomics identify thousands of potentially significant differences between individuals; and computational models are being used to predict which therapies will work for which patients. This course will focus on the applications of pharmacokinetics and pharmacodynamics to simulating the effects of various drugs across a heterogeneous population of diseased individuals. Such computational approaches are needed to harness and leverage the vast amounts of data and provide insight into the key differences that determine drug responsiveness. These approaches can also explore the temporal dynamics of disease and treatment, and enable the modification of treatment during recovery. Recommended background: 110.201 Linear Algebra, 110.302 Differential Equations, and 550.311 Probability and Statistics (or equivalent).
Instructor(s): F. Macgabhann
Area: Engineering.

EN.580.431. Introduction to Computational Medicine I. 4.0 Credits.
Computational medicine is an emerging discipline in which computer models of disease are developed, constrained using data measured from individual patients, and then applied to deliver precision health care. Introduction to Computational Medicine I is the first in a sequence of two courses on computational medicine. It covers the core concepts of computational physiological medicine and computational anatomy. The first half of this course will cover computational physiological medicine. Students will learn how to: use biophysical laws and data to formulate computational models of physiological systems in health and disease; analyze the behaviors of these models using analytical and simulation approaches; apply models to understand their use in diagnosing and treating disease. The second half of this course will cover computational anatomy. Students will learn how to: model anatomic variations using magnetic resonance imaging data; compare anatomic via mappings onto anatomical atlases; discover anatomic biomarkers of disease; analyze changes in the connectivity of anatomic data. Class time will emphasize hands-on learning through data analysis, software development, and simulation. All instructional materials will be made available at the beginning of the course. Recommended Course Background: C++, Matlab or Python.
Prerequisites: ( AS.110.107 OR AS.110.109 OR AS.110.113 ) AND ( EN.553.310 OR EN.580.311 OR EN.580.420 OR EN.580.430 )
Instructor(s): M. Miller; R. Winslow.
EN.580.434. Bioelectricity. 3.0 Credits.
This course has been revised to include numerous examples of bioelectrically active tissues and organs, complemented by relevant engineering principles. Topics include bioelectric currents and potentials, measurements of biological electric fields, wound repair in skin and epithelia, early history of bioelectricity, volume conductor theory, cardiac electrogam and lead theory, electromanipulation of cells, galvanotaxis, stem cell development, bone repair, and neuronal growth. Recommended Prereqs: EN.580.421 and EN.580.422.
Instructor(s): L. Tung
Area: Engineering.

EN.580.437. Neuro Data Design I. 4.0 Credits.
In this year long course, students will work together in small teams to design, develop, and deploy a functioning tool for practicing brain scientists, either for accelerating research or augmenting the clinic. The first semester will focus on scoping the tool, including determining feasibility (for us in a year) and significance (for the targeted brain science community), as well as a statement of work specifying deliverables and milestones. The second semester will focus on developing the tool, getting regular feedback, and iterating, using the agile/lean development process. Recommended Course Background: numerical programming.
Instructor(s): J. Vogelstein
Area: Engineering, Natural Sciences.

EN.580.438. Neuro Data Design II. 4.0 Credits.
In this year long course, students will work together in small teams to design, develop, and deploy a functioning tool for practicing brain scientists, either for accelerating research or augmenting the clinic. The first semester will focus on scoping the tool, including determining feasibility (for us in a year) and significance (for the targeted brain science community), as well as a statement of work specifying deliverables and milestones. The second semester will focus on developing the tool, getting regular feedback, and iterating, using the agile/lean development process. Recommended background: numerical programming.
Instructor(s): J. Vogelstein
Area: Engineering.

EN.580.439. Models of the Neuron. 4.0 Credits.
Single-neuron modeling, emphasizing the use of computational models as links between the properties of neurons at several levels of detail. Topics include thermodynamics of ion flow in aqueous environments, biology and biophysics of ion channels, gating, nonlinear dynamics as a way of studying the collective properties of channels in a membrane, synaptic transmission, integration of electrical activity in multi-compartment dendritic tree models, and properties of neural networks. Students will study the properties of computational models of neurons; graduate students will develop a neuron model using data from the literature. Recommended Course Background: AS.110.302 or equivalent.
Meets with EN.580.639
Instructor(s): R. Winslow; S. Sarma
Area: Engineering, Natural Sciences.

EN.580.441. Cellular Engineering. 3.0 Credits.
This course focuses on principles and applications in cell engineering. Class lectures include an overview of molecular biology fundamentals, protein/ligand binding, receptor/ligand trafficking, cell-cell interactions, cell-matrix interactions, and cell adhesion and migration at both theoretical and experimental levels. Lectures will cover the effects of physical (e.g. shear stress, strain), chemical (e.g. cytokines, growth factors) and electrical stimuli on cell function, emphasizing topics on gene regulation and signal transduction processes. Furthermore, topics in metabolic engineering, enzyme evolution, polymeric biomaterials, and drug and gene delivery will be discussed. This course is intended as Part 1 of a two-semester sequence recommended for students in the Cell and Tissue Engineering focus area. Recommended Course Background: EN.580.221 or AS.020.305 and AS.020.306 or equivalent and AS.030.205
Meets with EN.580.641
Instructor(s): J. Green; K. Yarema
Area: Engineering.

EN.580.442. Tissue Engineering. 3.0 Credits.
This course focuses on the application of engineering fundamentals to designing biological tissue substitutes. Concepts of tissue development, structure and function will be introduced. Students will learn to recognize the majority of histological tissue structures in the body and understand the basic building blocks of the tissue and clinical need for replacement. The engineering components required to develop tissue-engineered grafts will be explored including biomechanics and transport phenomena along with the use of biomaterials and bioreactors to regulate the cellular microenvironment. Emphasis will be placed on different sources of stem cells and their applications to tissue engineering. Clinical and regulatory perspectives will be discussed. Recommended Course Background: EN.580.221 or AS.020.305 and AS.020.306, AS.030.205 Recommended EN.580.441/EN.580.641 Co-listed with EN.580.642
Instructor(s): J. Elisseeff; W. Grayson
Area: Engineering.

EN.580.443. Advanced Orthopaedic Tissue Engineering. 3.0 Credits.
This course is intended to provide a comprehensive overview on the current state of the field of Orthopaedic Tissue Engineering. Students will apply engineering fundamentals learned in the Tissue Engineering course (EN.580.442/642) with special emphasis on how they apply to bone, cartilage, and skeletal muscle tissue engineering. The development, structure, mechanics, and function of each of these tissues will be discussed. Key articles from the last three decades that focus on stem cell- and cell-free, biomaterial-based approaches to regenerate functional tissues will be presented and analyzed. Practical (regulatory/commercial) considerations that restrict the translation of therapies to the clinic will be discussed.
Prerequisites: Grade of B or higher in EN.580.442 OR EN.580.642
Instructor(s): W. Grayson
Area: Engineering.
EN.580.444. Biomedical Applications of Glycoengineering. 3.0 Credits.
This course provides an overview of carbohydrate-based technologies in biotechnology and medicine. The course will begin by briefly covering basics of glycobiology and glycochemistry followed by detailed illustrative examples of biomedical applications of glycoengineering. A sample of these applications include the role of sugars in preventative medicine (e.g., for vaccine development and probiotics), tissue engineering (e.g., exploiting natural and engineered polysaccharides for creating tissue or organs de novo in the laboratory), regenerative medicine (e.g., for the treatment of arthritis or degenerative muscle disease), and therapy (e.g., cancer treatment). A major part of the course grade will be based on class participation with each student expected to provide a “journal club” presentation of a relevant paper as well as participate in a team-based project designed to address a current unmet clinical need that could be fulfilled through a glycoengineering approach. Recommended Course Background: EN.580.222 Molecules and Cells
Instructor(s): K. Yarema
Area: Engineering, Natural Sciences.

EN.580.445. Networks. 3.0 Credits.
Networks are ubiquitous in our modern society. The World Wide Web that links us to and enables information flows with the rest of the world is the most visible example. It is, however, only one of many networks within which we are situated. Our social life is organized around networks of friends and colleagues. These networks determine our information, influence our opinions, and shape our political attitudes. They also link us, often through important but weak ties, to everybody else in the United States and in the world. Economic and financial markets also look much more like networks than anonymous marketplaces. Firms interact with the same suppliers and customers and use Web-like supply chains. Financial linkages, both among banks and between consumers, companies and banks, also form a network over which funds flow and risks are shared. Systemic risk in financial markets often results from the counterparty risks created within this financial network. Food chains, interacting biological systems and the spread and containment of epidemics are some of the other natural and social phenomena that exhibit a marked networked structure. This course will introduce the tools for the study of networks. It will show how certain common principles permeate the functioning of these diverse networks and how the same issues related to robustness, fragility, and interlinkages arise in several different types of networks. Biological applications will be highlighted as material is presented. Recommended Course Background: EN.580.222
Instructor(s): S. Sarma
Area: Engineering.

EN.580.446. Physical Epigenetics. 3.0 Credits.
Epigenetics describes information heritable during cell division other than DNA sequence per se. Recent advances show the critical role of epigenetics in controlling gene expression, embryonic development, and common human diseases such as cancer. This course will introduce fundamental epigenetic principles with a focus on mechanisms, modeling, and physical principles, relationship to genetics, and application to understanding human disease mechanisms. Recommended Course Background: EN.580.221 Molecules and Cells or equivalent (molecular and cell biology), college level calculus and calculus-based general physics.
Instructor(s): A. Feinberg; T. Ha
Area: Engineering, Natural Sciences.

EN.580.448. Biomechanics of the Cell. 3.0 Credits.
Mechanical aspects of the cell are introduced using the concepts in continuum mechanics. We will discuss the role of proteins, membranes and cytoskeleton in cellular function and how to describe them using simple mathematical models. Co-listed with EN.530.410 Recommended course background: AS.171.101-102, AS.110.108-109 and AS.110.202
Instructor(s): A. Spector; S. Sun
Area: Engineering.

EN.580.451. Cell and Tissue Engineering Lab. 3.0 Credits.
Cell and tissue engineering is a field that relies heavily on experimental techniques. This laboratory course will consist of three six experiments that will provide students with valuable hands-on experience in cell and tissue engineering. Students will learn basic cell culture procedures and specialized techniques related to faculty expertise in cell engineering, microfluidics, gene therapy, microfabrication and cell encapsulation. Experiments include the basics of cell culture techniques, gene transfection and metabolic engineering, basics of cell-substrate interactions, cell-substrate interactions II, and cell encapsulation and gel contraction. Co-listed with EN.530.451. Senior and Graduate students only; others, instructor permission required. Fall semester only. Lab Fee: $100
Instructor(s): E. Haase
Area: Engineering, Natural Sciences.

EN.580.452. Cell and Tissue Engineering Lab. 3.0 Credits.
This laboratory course will consist of three experiments that will provide students with valuable hands-on experience in cell and tissue engineering. Experiments include the basics of cell culture techniques, gene transfection and metabolic engineering, basics of cell-substrate interactions I, cell-substrate interactions II, and cell encapsulation and gel contraction. Spring semester only.
Prerequisites: Students must have completed Lab Safety training prior to registering for this class.
Instructor(s): E. Haase
Area: Engineering, Natural Sciences.

EN.580.456. Introduction to Rehabilitation Engineering. 3.0 Credits.
The primary objective of this course is to introduce biomedical engineering students to the challenges of engineering solutions for persons functioning with disabilities. In order to achieve this goal, other objectives include: gaining a basic appreciation of the modalities used to treat impairments, the opportunities for application of engineering to improve treatment delivery, understanding the science and engineering applied to helping persons with disabilities function in the everyday world and an basic knowledge of the legal, ethical issues and employment opportunities in rehabilitation engineering. By the conclusion of this class, students should be able to: • Understand the breadth and scope of physical impairment and disability, including its associated pathophysiology • Characterize the material and design properties of current evaluation tools for assessment of impairments and adaptations for disability • Characterize the material and design properties of current modalities of treatment of impairments and adaptations for disability • Apply engineering analysis and design principles to critique current solutions for persons with disabilities in order to suggest improvements
Prerequisites: EN.580.422
Instructor(s): S. Paul
Area: Engineering.
EN.580.457. Rehabilitation Engineering Design Lab. 3.0 Credits.
The primary objective of this course is to give biomedical engineering students who have completed 580.456 (Intro to Rehab Engineering) the opportunity to apply the knowledge they have gained in that course and their prior coursework to the development of a new, improved device to be used for measurement or treatment of an impairment or disability. In doing so, they will learn the biomedical engineering design process and its application to persons with disabilities. Working in groups of four to five, teams will work on a project derived from a needs analysis based on their visits to rehabilitation centers in the fall semester. Project will require instructor approval before the beginning of the spring semester. Each project will consist of a proposal for design of a new device or solution to a problem faced by persons with disabilities, preliminary “virtual” (e.g., CAD), and actual proof of concept working prototype.

Prerequisites: EN.580.422
Instructor(s): S. Paul
Area: Engineering.

EN.580.460. Theory of Cancer. 3.0 Credits.
The course will deal with important problems in cancer and how they can be approached using mathematical and computational modeling. The course will be organized around introductory material describing the biological and clinical problem and the mathematical and computational methodology that will be used for its analysis. This will be followed by analysis of key modeling papers dealing with the problem. An important part of the course will be a computational modeling project (small group or individual) dealing with modeling of cancer in which the students will extend existing models or formulate novel models of cancer, including cancer therapeutics. The students will strive to create models leading to new discoveries.

Instructor(s): A. Popel
Area: Engineering.

EN.580.462. Representations of Choice. 3.0 Credits.
In this course we will examine key computational topics from the nascent fields of decision neuroscience and neuroeconomics. After taking this course students will have an understanding of how the field emerged and will develop a critical appreciation of the advantages and limitations of different analytical approaches. Students will also be able to discuss the current knowledge on processes of valuation, value-learning and decision-making in relation to their computational representations at the behavioral and neural level. Linear Algebra and programming experience (python, matlab, or C) recommended.

Instructor(s): V. Chib
Area: Engineering.

EN.580.466. Statistical Methods in Imaging. 3.0 Credits.
Denosing, segmentation, texture modeling, tracking, object recognition are challenging problems in imaging. We will present a collection of statistical models and methods in order to address these, including the E.M algorithm, Maximum Entropy Modeling, Markov Random Fields, Markov Chain Monte Carlo, Boltzmann Machines and MultiLayer Perceptrons. Recommended Course Background: AS.110.202 and EN.553.310 or equivalent.

Instructor(s): B. Jedynak
Area: Engineering, Quantitative and Mathematical Sciences.

EN.580.468. The Art of Data Science. 3.0 Credits.
In this course, we will cover the fundamentals of doing data science research, explaining "best practices" for each step, that collectively comprise an upward spiral. These steps include: (i) asking an interesting question, (ii) determining the degree to which the answer is known, (iii) assessing there currently exists data to likely obtain a satisfactory answer, (iv) exploring the data set, (v) cleaning up the dataset, (vi) formalizing a statistical inquiry, (vii) positing a statistical model which we hope will yield satisfactory answers, (viii) devising a test to assess the answer, (ix) building an estimator to assess the model, (x) checking the model, (xi) reporting the results, (xii) suggesting the next experiment to perform or question to answer to further enhance the model. Note that this course will largely be project based; each student will be expected to complete each of the above steps on some real data of interest to the student. Lectures will be minimal, giving introductory explanations one day, hopefully only part of the time. The rest of the time, we will work independently or in small groups to complete the weekly portion of the overall project. Please come ready to do science! If you don't have questions that you want answered, you can work in small groups, but each student will need to write the code and reports on their own. Recommended Course Background: No courses are formally required, though students will need to write numerical code (in R, Python, or Julia), and make reports using LaTeX, knitr, or Jupyter notebooks or similar.

Instructor(s): J. Vogelstein
Area: Engineering.

EN.580.471. Principles of Design of BME Instrumentation. 4.0 Credits.
This core design course will cover lectures and hands-on labs. The material covered will include fundamentals of biomedical sensors and instrumentation, FDA regulations, designing with electronics, biopotentials and ECG amplifier design, recording from heart, muscle, brain, etc., diagnostic and therapeutic devices (including pacemakers and defibrillators), applications in prosthetics and rehabilitation, and safety. The course includes extensive laboratory work involving circuits, electronics, sensor design and interface, and building complete biomedical instrumentation. The students will also carry out design challenge projects, individually or in teams (examples include “smart cane for blind,” “computer interface for quadriplegic”). Students satisfying the design requirement must also register for EN.580.571. Lab Fee: $150. Recommended Course Background: EN.520.345

Prerequisites: Students must have completed Lab Safety training prior to registering for this class.

Instructor(s): N. Thakor
Area: Engineering, Natural Sciences.

EN.580.472. Medical Imaging Systems. 3.0 Credits.
An introduction to the physics, instrumentation, and signal processing methods used in general radiography, X-ray computed tomography, ultrasound imaging, magnetic resonance imaging, and nuclear medicine. The primary focus is on the methods required to reconstruct images within each modality, with emphasis on the resolution, contrast, and signal-to-noise ratio of the resulting images. Cross-listed with Neuroscience and Electrical and Computer Engineering (EN.520.432).

Prerequisites: EN.580.222 OR EN.520.214

Instructor(s): M. Bell
Area: Engineering.
EN.580.473. Modern Biomedical Imaging Instrumentation and Techniques. 3.0 Credits.
An intermediate biomedical imaging course covering modern biomedical imaging instrumentation and techniques as applied to diagnostic radiology and other biomedical applications. It includes recent advances in various biomedical imaging modalities, multi-modality imaging and molecular imaging. The course is team taught by experts in the respective fields and provides a broad based knowledge of modern biomedical imaging to prepare students for graduate studies and research in biomedical imaging. Also, the course will offer tours and practical experience with modern biomedical imaging equipment in clinical and research settings. Co-listed with EN.520.434 Recommended course background: EN.520.432 or EN.580.472
Prerequisites: Students may not have taken EN.580.773.
Instructor(s): B. Tsui
Area: Engineering, Natural Sciences.

EN.580.476. Magnetic Resonance in Medicine. 3.0 Credits.
This course provides the student with a complete introduction to the physics of x-ray interaction and detection, image quality modeling and assessment, 3D image reconstruction (including analytical and iterative approaches), and applications in diagnostic and image-guided procedures. Recommended Course Background: EN.580.222 or EN.520.214. Co-listed with EN.580.673.
Instructor(s): M. Schar; P. Bottomley
Area: Engineering.

EN.580.479. X-ray Imaging and Computed Tomography. 3.0 Credits.
This course provides students with an intermediate-level understanding of the physics, engineering, algorithms, and applications of medical x-ray imaging and computed tomography (CT). It is intended for senior undergraduates (EN.580.479) and/or graduate students (EN.580.679) in Biomedical Engineering, Computer Science, Electrical and Computer Engineering, or related fields in science and engineering. Topics include the physics of x-ray interaction and detection, image quality modeling and assessment, 3D image reconstruction (including analytical and iterative approaches), and applications in diagnostic and image-guided procedures. Recommended Course Background: EN.580.472 and/or EN.580.473 and familiarity with Matlab.
Instructor(s): J. Siewersen
Area: Engineering.

EN.580.483. Nuclear Medicine Imaging. 3.0 Credits.
This course provides an intermediate-level introduction to the instrumentation, image processing and reconstruction methods used in planar nuclear medicine imaging, single-photon emission computed tomography (SPECT) and positron emission tomography (PET). Topics include radioactive decay, nuclear medicine instrumentation including radiation detectors and associated electronics, analytic and statistical iterative tomographic reconstruction, imaging physics, and image quality in the context of these three modalities. This course will be taught at the School of Medicine Campus. Recommended Course Background: EN.520.432/EN.580.472 and EN.520.434/EN.580.473
Instructor(s): A. Rahmim; B. Tsui; E. Frey; Y. Du
Area: Engineering.

EN.580.488. Foundations of Computational Biology and Bioinformatics II. 3.0 Credits.
This course will introduce probabilistic modeling and information theory applied to biological sequence analysis, focusing on statistical models of protein families, alignment algorithms, and models of evolution. Topics will include probability theory, score matrices, hidden Markov models, maximum likelihood, expectation maximization and dynamic programming algorithms. Homework assignments will require programming in Python. Foundations of Computational Biology I is not a prereq. Recommended Course Background: Math through linear algebra and differential equations, EN.580.221 or equivalent, EN.601.226 or equivalent
Instructor(s): R. Karchin
Area: Engineering, Natural Sciences.

EN.580.491. Learning Theory. 3.0 Credits.
The course introduces the probabilistic foundations of learning theory. We will discuss topics in regression, estimation, optimal control, system identification, Bayesian learning, and classification. Our aim is to first derive some of the important mathematical results in learning theory, and then apply the framework to problems in biology, particularly animal learning and control of action. Recommended Course Background: AS.110.201 and AS.110.302
Instructor(s): R. Shadmehr
Area: Engineering.

EN.580.492. Build-a-Genome Mentor. 4.0 Credits.
In addition to producing and sequencing DNA segments like regular B-a-G students, mentors will help prepare and distribute reagents, and maintain a Moddle site to track student reagent use and productivity. Mentors will also be expected to mentor specific students who are learning new techniques for the first time, contribute to the computational and biotech infrastructure associated with Build-a-Genome, and pursue at least one independent research project. Successful completion of this course provides 3 credit hours toward the supervised research requirement for Molecular and Cellular Biology majors. Co-listed AS.020.451 Permission Required.
Prerequisites: Students must have completed Lab Safety training prior to registering for this class.;
Instructor(s): J. Bader; K. Zeller
Area: Engineering, Natural Sciences.

EN.580.493. Imaging Instrumentation. 4.0 Credits.
This course is intended to introduce students to imaging instrumentation. The class will be lab-oriented, giving hands-on experience with data collection and processing using a configurable optical system. Specific topics will include the programming and control of electromechanical elements, imaging data acquisitions, image formation and processing (e.g. 3D reconstruction), and imaging system analysis and optimization. Recommended Course Background: EN.580.222 Systems and Controls or EN.520.214 Signals and Systems. Programming experience highly desirable.
Instructor(s): J. Stayman
Area: Engineering.

EN.580.495. Microfabrication Lab. 4.0 Credits.
This laboratory course introduces the principles used in the construction of microelectronic devices, sensors, and micromechanical structures. Students will work in the laboratory on the fabrication and testing of a device. Accompanying lecture material covers basic processing steps, design and analysis CAD tools, and national foundry services. Co-listed with EN.530.495 and EN.520.495 Seniors only. Permission Required.
Instructor(s): A. Andreou; J. Wang
Area: Engineering, Natural Sciences.
EN.580.501. Fall BME Research - Freshman/Sophomore. 3.0 Credits.  
Instructor(s): Staff.

EN.580.502. Spring BME Research - Freshman/Sophomore. 1.0 - 4.0 Credits.  
Practicum in Biomedical Engineering Research projects or engineering design projects under the supervision of any member of the BME faculty.  
Instructor(s): Staff.

EN.580.510. Biomedical Engineering Undergraduate Research. 1.0 - 3.0 Credits.  
Student participation in ongoing research activities. Research is conducted under the supervision of a faculty member and often in conjunction with other members of the research group.  
Instructor(s): Staff.

EN.580.511. Biomedical Engineering Undergraduate Research. 1.0 - 3.0 Credits.  
Student participation in ongoing research activities. Research is conducted under the supervision of a faculty member and often in conjunction with other members of the research group.  
Instructor(s): K. Yarema; M. Beer; R. Allen.

EN.580.512. Spring BME Independent Study - Freshman/Sophomore. 0.0 - 4.0 Credits.  
Directed readings or other literature research under the direction of any member of the BME faculty.  
Instructor(s): Staff.

EN.580.531. Fall BME Research - Junior/Senior. 3.0 Credits.  
Instructor(s): Staff.

EN.580.532. Spring BME Research - Junior/Senior. 3.0 Credits.  
Research projects or engineering design projects under the supervision of any member of the BME faculty.  
Instructor(s): Staff.

EN.580.541. Fall BME Independent Study - Junior/Senior. 3.0 Credits.  
Directed readings or other literature research under the direction of any BME faculty member.  Junior or Senior standing.  
Instructor(s): Staff.

EN.580.542. Spring BME Independent Study - Junior/Senior. 0.0 - 4.0 Credits.  
Directed readings or other literature research under the direction of any BME faculty member.  
Instructor(s): Staff.

EN.580.550. Biomedical Engineering Group Undergraduate Research. 1.0 - 3.0 Credits.  
Student participation in ongoing research activities. Research is conducted under the supervision of a faculty member and often in conjunction with other members of the research group.  
This section has a weekly research group meeting that students are expected to attend.  
Instructor(s): Staff.

EN.580.551. Biomedical Engineering Group Undergraduate Research. 1.0 - 3.0 Credits.  
Student participation in ongoing research activities. Research is conducted under the supervision of a faculty member and often in conjunction with other members of the research group.  
This section has a weekly research group meeting that students are expected to attend.  
Instructor(s): Staff.

EN.580.580. Senior Design Project. 3.0 Credits.  
Per independent or team design project to design and evaluate a system.  
The design should demonstrate creative thinking and experimental skills, and must draw upon advanced topics of biomedical and traditional engineering. Permission Required.  
Instructor(s): R. Allen; Y. Yazdi.

EN.580.581. Senior Design Project. 3.0 Credits.  
Independent or team design project to design and evaluate a system.  
The design should demonstrate creative thinking and experimental skills, and must draw upon advanced topics of biomedical and traditional engineering. Permission Required.  
Instructor(s): R. Allen.

EN.580.590. Biomedical Internship. 1.0 Credit.  
Instructor(s): Staff.

EN.580.595. BME Senior Design - Summer. 3.0 Credits.  
Instructor(s): J. Green; L. Schramm; R. Allen.

EN.580.597. BME Research - Summer. 3.0 Credits.  
Instructor(s): Staff.

EN.580.598. Design Project. 3.0 Credits.  
Instructor(s): R. Allen.

EN.580.599. Independent Study. 3.0 Credits.  
Instructor(s): A. Shoukas; H. Goldberg; K. Yarema; N. Thakor; S. Kuo.

EN.580.601. Special Topics in Bioengineering Innovation and Design. 1.0 Credit.  
This year long seminar series features experts from the medical device industry, venture capital firms, FDA, patent attorneys, entrepreneurs, and many more. They will share their real-world insights into the medical device innovation and commercialization process. Some of the topics covered will include bioethics, regulatory and reimbursement planning, medical device recalls, good design practices, and entrepreneurial success stories. The overarching philosophy of this seminar series is to complement the theoretical and practical aspects of the program curriculum, by learning from the experiences and insights of professionals in the field. These seminars are taken in a sequence of summer, fall, and spring. They are required for CBID masters students and are open to those students only.  
Instructor(s): S. Acharya.

EN.580.602. Special Topics in Bioengineering Innovation and Design. 1.0 Credit.  
This year long seminar series features experts from the medical device industry, venture capital firms, FDA, patent attorneys, entrepreneurs, and many more. They will share their real-world insights into the medical device innovation and commercialization process. Some of the topics covered will include bioethics, regulatory and reimbursement planning, medical device recalls, good design practices, and entrepreneurial success stories. The overarching philosophy of this seminar series is to complement the theoretical and practical aspects of the program curriculum, by learning from the experiences and insights of professionals in the field. For CBID MSE students only. Registration with instructor's permission only.  
Instructor(s): S. Acharya.
EN.580.603. Special Topics in Bioengineering Innovation & Design. 1.0 Credit.
This year long seminar series features experts from the medical device industry, venture capital firms, FDA, patent attorneys, entrepreneurs, and many more. They will share their real-world insights into the medical device innovation and commercialization process. Some of the topics covered will include bioethics, regulatory and reimbursement planning, medical device recalls, good design practices, and entrepreneurial success stories. The overarching philosophy of this seminar series is to complement the theoretical and practical aspects of the program curriculum, by learning from the experiences and insights of professionals in the field. For CBID MSE students only.
Instructor(s): S. Acharya.

EN.580.604. I: Business of Bioengineering Innovation and Design. 3.0 Credits.
This course comprises two distinct, but related, components. The first is a broad introduction to the terms, concepts, and values of business and management. Particular emphasis will be placed on the economic, financial, and corporate contexts of our business culture, and how they impact the organization, strategy, and decision-making of business firms. The second component is an introduction to the sociological and economic forces that shape the development and diffusion of new technologies. This part is primarily designed to provide a framework for determining the commercial viability of new medical devices and the best path for realizing their value, including how to develop a compelling value proposition, analyze markets and competitors, and protect intellectual property. Throughout, the course utilizes individual exercises, case analyses, and team projects.
Instructor(s): L. Aronhime.

EN.580.605. II: Business of Bioengineering Innovation and Design. 3.0 Credits.
This course comprises two distinct, but related, components. The first is a broad introduction to the terms, concepts, and values of business and management. Particular emphasis will be placed on the economic, financial, and corporate contexts of our business culture, and how they impact the organization, strategy, and decision-making of business firms. The second component is an introduction to the sociological and economic forces that shape the development and diffusion of new technologies. This part is primarily designed to provide a framework for determining the commercial viability of new medical devices and the best path for realizing their value, including how to develop a compelling value proposition, analyze markets and competitors, and protect intellectual property. Throughout, the course utilizes individual exercises, case analyses, and team projects.
Instructor(s): L. Aronhime.

EN.580.607. Regulation of Medical Devices. 1.0 Credit.
This course introduces graduate students in Bioengineering Innovation and Design to the medical device regulatory framework, as it pertains to bringing a medical device from concept to market. Topics covered include: FDA Design Controls; Regulatory Approval mechanisms, including the 510k and PMA process; Investigational Device exemption (IDE); planning clinical trials needed for bringing a medical device to market; and postmarket surveillance. Students learn from a series of invited lecturers from the FDA as well as professionals from the medical device industry. This summer course is required for CBID masters students and is not open to any other students.
Instructor(s): S. Acharya.

EN.580.608. Identification and Validation of Medical Device Needs. 6.0 Credits.
This course teaches the art and skill of identifying medical device opportunities by experiencing real world scenarios in an immersive clinical environment. Students rotate through multiple clinical disciplines and become part of the team of senior clinicians, surgeons, residents, fellows, nurses and medical technologists. They learn to identify unmet medical device needs through direct observations in a variety of clinical settings including the hospital ward and operating room, interviews (with patients, doctors, nurses, hospital administration), literature survey, and more. Concurrently, they learn the process of filtering all observations to a few valid medical device opportunities by assessing the market size, intellectual property landscape, regulatory framework, and competitor dynamics in addition to the clinical impact that such a device could have. The ability to identify a relevant medical device need is an important first step in the medical device innovation cycle; this course aims to provide students with practical hands-on training in that process.
Instructor(s): C. Weiss; H. Nguyen; S. Acharya.

EN.580.609. BME Teaching Practicum. 3.0 Credits.
Instructor(s): E. Haase.

EN.580.611. Medical Device Design and Innovation. 4.0 Credits.
For CBID MSE students only. Registration with instructor's permission only.
Instructor(s): S. Acharya.

EN.580.612. Medical Device Design and Innovation. 4.0 Credits.
For CBID MSE students only.
Instructor(s): S. Acharya.

EN.580.618. Needs Identification and Validation for Global Health Innovation. 4.0 Credits.
Limited to CBID students only
Instructor(s): S. Acharya.

EN.580.619. Bioengineering Innovation and Design - Global Health. 4.0 Credits.
For CBID MSE students only. Registration with instructor's permission only.
Instructor(s): S. Acharya.

EN.580.620. Principles and Practice of Global Health Innovation and Design. 4.0 Credits.
For CBID MSE students only. Instructor’s Permission Required.
Instructor(s): S. Acharya.

EN.580.621. Insight Informed Innovation I. 3.0 Credits.
For CBID MSE students only. Registration with instructor’s permission only.
Instructor(s): B. Craft; P. Fearis.

EN.580.623. Insight Informed Innovation II. 3.0 Credits.
This course is intended to equip students with a structured process and the tools required to: 1. Identify opportunities for new medical devices through unmet, unarticulated and underserved stakeholder needs. 2. Link these insights to an exhaustive set of potential solutions. 3. Synthesize solutions and features into product concepts. Recommended Course Background: Insight Informed Innovation I (summer)
Instructor(s): B. Craft; P. Fearis.
EN.580.625. Structure and Function of the Auditory and Vestibular Systems. 3.0 Credits.
This course will cover basic functions of the auditory and vestibular pathways responsible for perception of sound and balance. Topics include: hair cell structure and mechanotransduction, hair cell electromotility and cochlear active force production, hair cell synaptic signaling, cochlear development and role of glia in the inner ear, primary auditory and vestibular stimulus encoding, afferents and the first-order brainstem nuclei, as well as clinical consequences of peripheral damage, physiology of hearing loss, vestibular loss, tinnitus, hair cell regeneration and gene therapy. Moving more centrally, synaptic transmission and signal processing in central neurons, and complex sound perception and movement control will be discussed. Aspects such as speech perception, sound localization, vestibular reflexes, vestibular compensation, and self-motion perception are discussed with an integrated perspective covering perceptual, physiological, and mechanistic data. Grades will be based on participation in class, homework, and first-half and second-half exams (both in class, closed book, short answer/essay types). Offered in odd-numbered years. This course will meet in 529 Ross Research Bldg. at the School of Medicine campus. Recommended Background: general introduction to Neuroscience. Undergraduates with knowledge in Neuroscience welcome.
Instructor(s): E. Glowatzki; P. Fuchs.

EN.580.626. Structure & Function of the Auditory and Vestibular Brain. 3.0 Credits.
Brain mechanisms and perception of sound and balance. This course is an accompaniment for EN.580.625, although the courses can be taken in either order. Topics include representation of sound and balance in neural discharge patterns, anatomy of the central auditory and vestibular systems, synaptic transmission and signal processing in central neurons, and complex sound perception and movement control. Aspects such as speech perception, sound localization, vestibular reflexes and vestibular compensation are discussed with an integrated perspective covering perceptual, physiological, and mechanistic data. Recommended Course Background: EN.580.222 and EN.580.422 or equivalent. Taught at the School of Medicine, Taylor Bldg. 529.
Instructor(s): X. Wang.

EN.580.628. Topics in Systems Neuroscience. 1.0 Credit.
This course consists of weekly discussions of current literature in systems neuroscience. The selected readings will focus on neural mechanisms for perception, attention, motor behavior, learning, and memory, as studied using physiological, psychophysical, computational, and imaging techniques. Students are expected to give presentations and participate in discussions. Recommended Course Background: AS.110.302, EN.520.214, EN.580.421 or equivalent Students will have to attend the organizational meeting to be able to enroll. The course is run by the Neuroscience department. Enrollment numbers may be limited by the course directors, and priority will be given to Neuroscience graduate students. Please contact the Neuroscience department for more information and the date of the organizational meeting.
Instructor(s): K. Zhang; X. Wang.

EN.580.630. Theoretical Neuroscience. 3.0 Credits.
Theoretical methods for analyzing information encoding and functional representations in neural systems. Models of single and multiple neural spike trains based on stochastic processes and information theory; detection and estimation of behaviorally relevant parameters from spike trans; system theoretic methods for analyzing sensory receptive fields; network models of neural systems. Both theoretical methods and the properties of specific well-studied neural systems will be discussed. Recommended Course Background: EN.580.422 or equivalent, EN.553.420 or equivalent, EN.580.222 or equivalent.
Instructor(s): K. Zhang; X. Wang.

EN.580.631. Introduction to Computational Medicine I. 4.0 Credits.
Computational medicine is an emerging discipline in which computer models of disease are developed, constrained using data measured from individual patients, and then applied to deliver precision health care. Introduction to Computational Medicine I is the first in a sequence of two courses on computational medicine. It covers the core concepts of computational physiological medicine and computational anatomy. The first half of this course will cover computational physiological medicine. Students will learn how to: use biophysical laws and data to formulate computational models of physiological systems in health and disease; analyze the behaviors of these models using analytical and simulation approaches; apply models to understand their use in diagnosing and treating disease. The second half of this course will cover computational anatomy. Students will learn how to: model anatomies using magnetic resonance imaging data; compare anatomies via mappings onto anatomical atlases; discover anatomical biomarkers of disease; analyze changes in the connectivity of anatomies in disease. Class time will emphasize hands-on learning through data analysis, software development, and simulation. All instructional materials will be made available at the beginning of the course. Recommended Course Background: C++, Matlab or Python.
Instructor(s): M. Miller; R. Winslow.

EN.580.632. Ionic Channels in Excitable Membranes. 3.0 Credits.
Ion channels are key signaling molecules that support electrical communication throughout the body. As such, these channels are a central focus of biomedical engineering as it relates to neuroscience, computational biology, biophysics, and drug discovery. The course introduces the engineering and molecular strategies used to understand the function of ionic channels. The course also surveys key papers that paint the current picture of how ion channels open and conduct ions. Biological implications of these properties are emphasized throughout. Finally, the course introduces how optical and electrophysiological methods now promise to revolutionize understanding of ionic channels. This course can be seen as a valuable partner of Models of the Neuron (EN.580.439). Recommended Course Background: EN.580.421 and EN.580.422 or equivalent, AS.110.201, AS.110.302
Instructor(s): D. Yue
Area: Engineering, Natural Sciences.
EN.580.638. Neuro Data Design II. 4.0 Credits.
In this year long course, students will work together in small teams to design, develop, and deploy a functioning tool for practicing brain scientists, either for accelerating research or augmenting the clinic. The first semester will focus on scouting the tool, including determining feasibility (for us in a year) and significance (for the targeted brain science community), as well as a statement of work specifying deliverables and milestones. The second semester will focus on developing the tool, getting regular feedback, and iterating, using the agile/lean development process. Recommended background: numerical programming.
Instructor(s): J. Vogelstein.

EN.580.639. Models of the Neuron. 4.0 Credits.
See description for EN.580.439. Differs in that an advanced modeling project using data from the literature is required. Graduate version of EN.580.439. Recommended Course Background: AS.110.302 or equivalent.
Instructor(s): R. Winslow; S. Sarma.

EN.580.640. Systems Pharmacology and Personalized Medicine. 3.0 Credits.
We have moved beyond the 'one-size-fits-all' era of medicine. Individuals are different, their diseases are different, and their responses to drugs are different too. This variability is not just from person to person; heterogeneity is observed even between tumors within the same person, and between sites within the same tumor. These levels of variability among the human population must be accounted for to improve patient outcomes and the efficiency of clinical trials. Some of the ways in which this is being explored include: drugs are being developed hand-in-hand with the tests needed to determine whether or not they will be effective; tumor fragments excised from patients are being cultured in the lab for high-throughput testing of drugs and drug combinations; data-rich assays such as genomics and proteomics identify thousands of potentially significant differences between individuals; and computational models are being used to predict which therapies will work for which patients. This course will focus on the applications of pharmacokinetics and pharmacodynamics to simulating the effects of various drugs across a heterogeneous population of diseased individuals. Such computational approaches are needed to harness and leverage the vast amounts of data and provide insight into the key differences that determine drug responsiveness. These approaches can also explore the temporal dynamics of disease and treatment, and enable the modification of treatment during recovery.
Recommended background: 110.201 Linear Algebra, 110.302 Differential Equations, and 550.311 Probability and Statistics (or equivalent).
Instructor(s): F. Macgabhann.

EN.580.641. Cellular Engineering. 3.0 Credits.
This course focuses on principles and applications in cell engineering. Class lectures include an overview of molecular biology fundamentals, protein/ligand binding, receptor/ligand trafficking, cell-cell interactions, cell-matrix interactions, and cell adhesion and migration at both theoretical and experimental levels. Lectures will cover the effects of physical (e.g. shear stress, strain), chemical (e.g. cytokines, growth factors) and electrical stimuli on cell function, emphasizing topics on gene regulation and signal transduction processes. Furthermore, topics in metabolic engineering, enzyme evolution, polymeric biomaterials, and drug and gene delivery will be discussed. This course is intended as Part 1 of a two-semester sequence recommended for students in the Cell and Tissue Engineering focus area. Meets with EN.580.441. Recommended Course Background: EN.580.221 or AS20.305 and AS.020.306 (or equivalent) and AS.030.205
Instructor(s): J. Green; K. Yarema.

EN.580.642. Tissue Engineering. 3.0 Credits.
This course focuses on the application of engineering fundamentals to designing biological tissue substitutes. Concepts of tissue development, structure and function will be introduced. Students will learn to recognize the majority of histological tissue structures in the body and understand the basic building blocks of the tissue and clinical need for replacement. The engineering components required to develop tissue-engineered grafts will be explored including biomechanics and transport phenomena along with the use of biomaterials and bioreactors to regulate the cellular microenvironment. Emphasis will be placed on different sources of stem cells and their applications to tissue engineering. Clinical and regulatory perspectives will be discussed. Co-listed with EN.580.641.
Recommended Course Background: EN.580.221 or AS20.305 and AS.020.306, AS.030.205, EN.580.441/EN.580.641
Instructor(s): J. Elisseeff; W. Grayson
Area: Engineering.

EN.580.643. Advanced Orthopaedic Tissue Engineering. 3.0 Credits.
This course is intended to provide a comprehensive overview on the current state of the field of Orthopaedic Tissue Engineering. Students will apply engineering fundamentals learned in the Tissue Engineering course (580.442/580.642) with special emphasis on how they apply to bone, cartilage, and skeletal muscle tissue engineering. The development, structure, mechanics, and function of each of these tissues will be discussed. Key articles from the last three decades that focus on stem cell- and cell-free, biomaterial-based approaches to regenerate functional tissues will be presented and analyzed. Practical (regulatory/commercial) considerations that restrict the translation of therapies to the clinic will be discussed. Undergraduate by permission only. Recommend Course Background: EN.580.442 or EN.580.642.
Instructor(s): W. Grayson.
EN.580.644. Biomedical Applications of Glycoengineering. 3.0 Credits.  
This course provides an overview of carbohydrate-based technologies in biotechnology and medicine. The course will begin by briefly covering basics of glycobiology and glycochemistry followed by detailed illustrative examples of biomedical applications of glycoengineering. A sample of these applications include the role of sugars in preventative medicine (e.g., for vaccine development and probiotics), tissue engineering (e.g., exploiting natural and engineered polysaccharides for creating tissue or organs de novo in the laboratory), regenerative medicine (e.g., for the treatment of arthritis or degenerative muscle disease), and therapy (e.g., cancer treatment). A major part of the course grade will be based on class participation with each student expected to provide a “journal club” presentation of a relevant paper as well as participate in a team-based project designed to address a current unmet clinical need that could be fulfilled through a glycoengineering approach.  
Recommended Course Background: EN.580.221 Molecules and Cells or equivalent (molecular and cell biology), college level calculus and calculus-based general physics.  
Instructor(s): K. Yarema  
Area: Engineering, Natural Sciences.

EN.580.646. Molecular Immunoengineering. 3.0 Credits.  
An in-depth study of the use of biomolecular engineering tools and techniques to manipulate immune function for clinical translation. The course will begin with a brief overview of the immune system, placing a particular emphasis on the molecular-level interactions that determine phenotypic outcomes. The remainder of the curriculum will address ways in which integrative approaches incorporating biochemistry, structural biophysics, molecular biology, and engineering have been used either to stimulate the immune response for applications in cancer and infectious disease, or to repress immune activation for autoimmune disease therapy. Recommended background: Biochemistry and Cell Biology or the BME Molecules and Cells. Those without recommended background should contact the instructor prior to enrolling.  
Instructor(s): J. Spangler  
Area: Engineering, Natural Sciences.

EN.580.656. Introduction to Rehabilitation Engineering. 3.0 Credits.  
The primary objective of this course is to introduce biomedical engineering students to the challenges of engineering solutions for persons functioning with disabilities. In order to achieve this goal, other objectives include: gaining a basic appreciation of the modalities used to treat impairments, the opportunities for application of engineering to improve treatment delivery, understanding the science and engineering applied to helping persons with disabilities function in the everyday world and an basic knowledge of the legal, ethical issues and employment opportunities in rehabilitation engineering. By the conclusion of this class, students should be able to: understand the breadth and scope of physical impairment and disability, including its associated pathophysiology; characterize the material and design properties of current evaluation tools for assessment of impairments and adaptations for disability; characterize the material and design properties of current modalities of treatment of impairments and adaptations for disability; apply engineering analysis and design principles to critique current solutions for persons with disabilities in order to suggest improvements.  
Instructor(s): S. Paul  
Area: Engineering.

EN.580.668. The Art of Data Science. 3.0 Credits.  
In this course, we will cover the fundamentals of doing data science research, explaining “best practices” for each step, that collectively comprise an upward spiral. These steps include: (i) asking an interesting question, (ii) determining the degree to which the answer is known, (iii) assessing there currently exists data to likely obtain a satisfactory answer, (iv) exploring the data set, (v) cleaning up the dataset, (vi) formalizing a statistical inquiry, (vii) positing a statistical model which we hope will yield satisfactory answers, (viii) devising a test to assess the answer, (ix) building an estimator to assess the model, (x) checking the model, (xi) reporting the results, (xii) suggesting the next experiment to perform or question to answer to further enhance the model. Note that this course will largely be project based; each student will be expected to complete each of the above steps on some real data of interest to the student. Lectures will be minimal, giving introductory explanations one day, hopefully only part of the time. The rest of the time, we will work independently or in small groups to complete the weekly portion of the overall project. Please come ready to do science! If you don’t have questions that you want answered, you can work in small groups, but each student will need to write the code and reports on their own. Recommended background: No courses are formally required, though students will need to write numerical code (in R, Python, or Julia), and make reports using LaTeX, knitr, or Jupyter notebooks or similar.  
Instructor(s): J. Vogelstein  
Area: Engineering.

EN.580.673. Magnetic Resonance in Medicine. 3.0 Credits.  
This course provides the student with a complete introduction to the physical principles, hardware design, and signal processing used in magnetic resonance imaging and magnetic resonance spectroscopy. The course is designed for students who wish to pursue research in magnetic resonance. Recommended course background: EN.580.222 or EN.520.214. Co-listed with EN.580.476.  
Instructor(s): M. Schar; P. Bottomley.

EN.580.678. Biomedical Photonics. 3.0 Credits.  
This course will cover the basic optics principles including geometric, beam and wave description of light. The course will also cover the basic generation and detection techniques of light and the principles of optical imaging and spectroscopy. After the basis is established, we will focus on some commonly employed optical techniques and tools for biomedical research including various optical microscopy technologies, fiber optics, Raman spectroscopy, Fluorescence (lifetime), FRAT, FRET and FCS. The recent development in tissue optics, biomedical optical imaging/spectroscopy techniques (such as OCT, multiphoton fluorescence and harmonics microscopy, Structured illumination, light scattering, diffuse light imaging and spectroscopy, optical molecular imaging, photo-acoustic imaging) will also be discussed. Representative biomedical applications of translational biomedical photonics technologies will be integrated into the corresponding chapters.  
Instructor(s): X. Li  
Area: Engineering.
EN.580.679. X-ray Imaging and Computed Tomography. 3.0 Credits.
This course provides students with an intermediate-level understanding of the physics, engineering, algorithms, and applications of medical x-ray imaging and computed tomography (CT). It is intended for senior undergraduates (EN.580.479) and/or graduate students (EN.580.679) in Biomedical Engineering, Computer Science, Electrical and Computer Engineering, or related fields in science and engineering. Topics include the physics of x-ray interaction and detection, image quality modeling and assessment, 3D image reconstruction (including analytical and iterative approaches), and applications in diagnostic and image-guided procedures. Recommended Course Background: EN.580.472 and/or EN.580.473 and familiarity with Matlab. Instructor(s): J. Siewerdsen
Area: Engineering.

EN.580.683. Nuclear Medicine Imaging. 3.0 Credits.
This course provides an intermediate-level introduction to the instrumentation, image processing and reconstruction methods used in planar nuclear medicine imaging, single-photon emission computed tomography (SPECT) and positron emission tomography (PET). Topics include radioactive decay, nuclear medicine instrumentation including radiation detectors and associated electronics, analytic and statistical iterative tomographic reconstruction, imaging physics, and image quality in the context of these three modalities. This course will be taught at the School of Medicine Campus. Recommended Course Background: EN.520.432/EN.580.472 or EN.520.434/EN.580.473
Instructor(s): A. Rahmim, B. Tsui; E. Frey; Y. Du
Area: Engineering.

EN.580.684. Ultrasound Imaging: Theory and Applications. 3.0 Credits.
This course is designed to teach students the theory behind ultrasound imaging and provide an opportunity to apply this theory in a final project. The projects will be centered around advanced beamformers, photoacoustic imaging and thermal imaging. Recommended course background: EN.520.432 or EN.580.472 or equivalent.
Instructor(s): E. Boctor.

EN.580.688. Foundations of Computational Biology & Bioinformatics II. 3.0 Credits.
This course will introduce probabilistic modeling and information theory applied to biological sequence analysis, focusing on statistical models of protein families, alignment algorithms, and models of evolution. Topics will include probability theory, score matrices, hidden Markov models, maximum likelihood, expectation maximization and dynamic programming algorithms. Homework assignments will require programming in Python. Recommended Course Background: Math through linear algebra and differential equations, EN.580.221 or equivalent, EN.601.226 or equivalent.
Instructor(s): R. Karchin.

EN.580.689. Computational Personal Genomics. 3.0 Credits.
What can we learn from the genome sequence of an individual? Genomic technology now makes it possible to generate huge amounts of DNA sequence data for a single individual at a relatively low cost. To make sense of this data, we need to employ sophisticated computational methods to identify genetic variations that influence an individual’s health. In this course, we will first review the state of the art in sequencing technology, and discuss how this technology is being applied to study human biology and disease. We will then explore the computational methods used to turn raw sequence data into knowledge. Topics will include genetic variant detection; discovery of chromosomal rearrangements and fusions; methods to measure gene expression from RNA; and measurements of the microbiome living inside our bodies. Recommended Course Background: EN.601.447/639, EN.600.363/463, EN.600.688, EN.580.688 (any one is sufficient), or permission of the instructor. Course is also open to undergraduate students.
Instructor(s): S. Salzberg
Area: Engineering.

EN.580.691. Learning Theory. 3.0 Credits.
This course introduces the probabilistic foundations of learning theory. We will discuss topics in regression, estimation, Kalman filters, Bayesian learning, classification, reinforcement learning, and active learning. Our focus is on iterative rather than batch methods for parameter estimation. Our aim is to use the mathematical results to model learning processes in the biological system. Recommended Course Background: Probability and Linear Algebra.
Instructor(s): R. Shadmehr.

EN.580.693. Imaging Instrumentation. 4.0 Credits.
This course is intended to introduce students to imaging instrumentation. The class will be lab-oriented, giving hands-on experience with data collection and processing using a configurable optical system. Specific topics will include the programming and control of electromechanical elements, imaging data acquisitions, image formation and processing (e.g. 3D reconstruction), and imaging system analysis and optimization. Recommended Course Background: EN.580.222 Systems and Controls or EN.520.214 Signals and Systems. Programming experience highly desirable.
Instructor(s): J. Stayman.

EN.580.694. Statistical Connectomics. 3.0 Credits.
This course will cover the basics of an exciting emerging field of statistical connectomics (aka, brain-graphs). It is so new, that we are going to make some of it up in this class! The first week will be introductory lectures that I give. The rest of the semester will be run like a seminar; each week will focus on a different topic. On Tuesdays we will hear about a statistical method that operates on graphs, and on Thursdays we will read about some neuroscience data upon which one could apply these techniques. The final project will consist of implementing a statistical method devised for graphs on a brain-graph problem. Recommended background: coursework in probability, linear algebra, and numerical programming (eg, R, Python, Matlab).
Instructor(s): J. Vogelstein
Area: Engineering.
EN.580.697. Neuro Data Design I. 4.0 Credits.
In this year long course, students will work together in small teams to design, develop, and deploy a functioning tool for practicing brain scientists, either for accelerating research or augmenting the clinic. The first semester will focus on building the tool, including determining feasibility (for us in a year) and significance (for the targeted brain science community), as well as a statement of work specifying deliverables and milestones. The second semester will focus on developing the tool, getting regular feedback, and iterating, using the agile/lean development process. Recommended Course Background: numerical programming.
Instructor(s): J. Vogelstein.

EN.580.701. CBID Masters Advanced Project. 3.0 - 10.0 Credits.
For second year CBID students.
Instructor(s): S. Acharya.

EN.580.702. CBID Masters Advanced Project. 3.0 - 10.0 Credits.
Instructor(s): S. Acharya.

EN.580.706. Introduction to Biomedical Rodent Surgery Laboratory and Grantsmanship. 3.0 Credits.
This course has been specifically designed for students interested in understanding the translational aspects of biomedical research and pursuing research as a career. The course aims to introduce diverse yet interlinked research concepts that will equip students with the necessary knowledge and expertise to independently carry out research endeavors in the future. A part of the course includes supervised hands-on in vivo workshops, in which students will learn basic rodent anatomy, physiology and some general experimental procedures. A second component will introduce research methodology, which will enable students to develop their scientific thought process and enhance their critical thinking skills through formulating hypothesis, developing aims, searching PubMed for related literature, understanding ethical guidelines and other regulatory issues. In today's scenario, scientists also need to have a strong communication ability to ensure that their research is accessible at a global platform. This requires skill and knowledge of scientifically drafting manuscripts, writing grants and articulating business plans as well as effectively presenting their research results (presentation, poster, etc.). We will allocate necessary time to develop this science-art as well. Students' attendance and active participation will enrich this exciting and interactive course, which is entirely based on in-class learning.
Instructor(s): A. All.

EN.580.721. Systems Bioengineering I. 4.0 Credits.
A quantitative, model-oriented investigation of the cardiovascular system. Topics are organized in three segments. (1) Molecular/cellular physiology, including electrical signaling and muscle contraction. (2) Systems cardiovascular physiology, emphasizing circuit-diagram analysis of hemodynamics. (3) Cardio-vascular horizons and challenges for biomedical engineers, including heart failure and its investigation/treatment by computer simulation, by gene-array analysis, by stem-cell technology, and by mechanical devices (left-ventricular assist and total-heart replacement). Recommended Course Background: EN.580.221 and EN.580.222
Instructor(s): N. Trayanova.

EN.580.722. Systems Bioengineering II. 4.0 Credits.
A quantitative, model-oriented approach to the study of the nervous system. Topics include functional anatomy of the central and autonomic nervous systems, neurons and networks, learning and memory, structure and function of the auditory and visual systems, motor systems, and neuro-engineering. Recommended Course Background: EN.580.221, EN.580.222, EN.580.223, AS.110.302, EN.580.421; Corequisite: EN.580.424
Instructor(s): X. Wang.

EN.580.727. Cell Engineering and Regenerative Medicine Seminar Series. 1.0 Credit.
Top researchers from around the world will present the latest research on stem cell science and clinical application followed by discussion. School of Medicine campus: PCTB, Mountcastle Auditorium
Instructor(s): J. Elisseeff.

EN.580.728. Advanced Seminar in Chemical Glycobiology & Carbohydrate Drug Design. 1.0 Credit.
This course uses the current literature to teach advanced topics in carbohydrate engineering. Students will be required to read current papers, selected textbook chapters and online content to prepare for interactive teaching sessions with faculty and other students. Potential topics will include: sugars as information storage entities and signaling molecules; methods to manipulate and characterize complex carbohydrates in vivo, through chemoenzymatic methods, and emerging high-throughput methodology; carbohydrate-based drug development; and the role of sugars in stem cell biology and tissue engineering. Evaluation will be both by faculty and fellow students. Graduate Level. Seniors by permission. Fall semester only.
Instructor(s): K. Yarema.

EN.580.729. Advanced Seminar in Chemical Glycobiology & Carbohydrate Drug Design. 1.0 Credit.
This course uses the current literature to teach advanced topics in carbohydrate engineering. Students will be required to read current papers, selected textbook chapters and online content to prepare for interactive teaching sessions with faculty and other students. Potential topics will include: sugars as information storage entities and signaling molecules; methods to manipulate and characterize complex carbohydrates in vivo, through chemoenzymatic methods, and emerging high-throughput methodology; carbohydrate-based drug development; and the role of sugars in stem cell biology and tissue engineering. Evaluation will be both by faculty and fellow students. Spring semester only.
Instructor(s): K. Yarema.

EN.580.736. Distinguished Seminar Series in Computational Medicine. 1.0 Credit.
We live in a new era in the understanding, diagnosis and treatment of human disease. Over the past ten years, extraordinary advances in modeling and computing technologies have opened the door to an array of possibilities that were previously beyond the reach of biomedical researchers. Today's powerful computational platforms are allowing us to begin to identify, analyze, and compare the fundamental biological components and processes that regulate human diseases and their impact on the body. The next step, then, is to harness the potential of these theoretical and computational tools and theory in a meaningful way -that is, to apply this "new medicine" to the exploration and treatment of many of our current diseases. This lecture series will feature world experts in computational medicine as well as laboratories at JHU's institute for Computational Medicine (ICM). Fall semester only. S/U grading only.
Instructor(s): F. Macgabhann; S. Sarma.
EN.580.737. Distinguished Seminar Series in Computational Medicine. 1.0 Credit.
We live in a new era in the understanding, diagnosis and treatment of human disease. Over the past ten years, extraordinary advances in modeling and computing technologies have opened the door to an array of possibilities that were previously beyond the reach of biomedical researchers. Today’s powerful computational platforms are allowing us to begin to identify, analyze, and compare the fundamental biological components and processes that regulate human diseases and their impact on the body. The next step, then, is to harness the potential of these theoretical and computational tools and theory in a meaningful way—that is, to apply this “new medicine” to the exploration and treatment of many of our current diseases. This lecture series will feature world experts in computational medicine as well as laboratories at JHU’s institute for Computational Medicine (ICM). Spring semester only.
Instructor(s): F. Macgabhann; S. Sarma.

EN.580.738. Advanced Seminars in Cardiac Electrophysiology and Mechanics. 1.0 Credit.
This course uses the current literature to teach advanced topics in cardiac electrophysiology and mechanics. Students will be required to read current articles and then conduct interactive teaching sessions with faculty and other students. Potential topics will include: ion channels, cardiac excitation-contraction coupling, myofilament regulation, cardiac arrhythmias, heart failure, therapies for arrhythmias and pump dysfunction. Evaluation will be both by faculty and fellow students. Graduate Level. Seniors by permission. Fall semester only.
Instructor(s): N. Trayanova; P. Boyle.

EN.580.739. Advanced Seminars in Cardiac Electrophysiology and Mechanics. 1.0 Credit.
This course uses the current literature to teach advanced topics in cardiac electrophysiology and mechanics. Students will be required to read current articles and then conduct interactive teaching sessions with faculty and other students. Potential topics will include: ion channels, cardiac excitation-contraction coupling, myofilament regulation, cardiac arrhythmias, heart failure, therapies for arrhythmias and pump dysfunction. Evaluation will be both by faculty and fellow students. Graduate Level. Seniors by permission only (signed add/drop form). Spring semester only.
Instructor(s): N. Trayanova; P. Boyle.

EN.580.746. Imaging Science Seminar. 1.0 Credit.
Fall semester only.
Instructor(s): M. Miller; R. Vidal.

EN.580.747. Imaging Science Seminar. 1.0 Credit.
Spring semester only.
Instructor(s): M. Miller; R. Vidal.

EN.580.748. Advanced Seminars in Magnetic Resonance Imaging. 3.0 Credits.
This course uses the current literature to teach advanced topics in magnetic resonance imaging. Students will be required to read current papers, selected textbook chapters and online content to prepare for interactive teaching sessions with faculty and other students. Potential topics will include: image artifacts, effect of motion, resolution and SNR, realtime imaging, clinical applications. Evaluation will be both by faculty and fellow students. Graduate Level. Seniors by permission. Fall semester only.
Instructor(s): E. McVeigh.

EN.580.749. Advanced Seminars in Magnetic Resonance Imaging. 3.0 Credits.
This course uses the current literature to teach advanced topics in magnetic resonance imaging. Students will be required to read current papers, selected textbook chapters and online content to prepare for interactive teaching sessions with faculty and other students. Potential topics will include: image artifacts, effect of motion, resolution and SNR, realtime imaging, clinical applications. Evaluation will be both by faculty and fellow students. Spring semester only.
Instructor(s): D. Herzka.

EN.580.771. Principles of the Design of Biomedical Instrumentation. 4.0 Credits.
This course is designed for graduate students interested in learning basic biomedical instrumentation design concepts and translating these into advanced projects based on their research on current state-of-the-art. They will first gain the basic knowledge of instrumentation design, explore various applications, and critically gain hands-on experience through laboratory and projects. At the end of the course, students would get an excellent awareness of biological or clinical measurement techniques, design of sensors and electronics (or electromechanical/chemical, microprocessor system and their use). They will systematically learn to design instrumentation with a focus on the use of sensors, electronics to design a core instrumentation system such as an ECG amplifier. Armed with that knowledge and lab skills, students will be encouraged to discuss various advanced instrumentation applications, such as brain monitor, pacemaker/defibrillator, or prosthetics. Further, they will be “challenged” to come up with some novel design ideas and implement them in a semester-long design project. Students will take part in reading the literature, learning about the state-of-the-art through journal papers and patents, and discussing, critiquing, and improving on these ideas. Finally, they will be implementing a selected idea into a semester-long advanced group project. Meets with 580.471 Graduate students only.
Instructor(s): N. Thakor.

EN.580.773. Modern Biomedical Imaging Instrumentation and Techniques. 3.0 Credits.
An intermediate biomedical imaging course covering modern biomedical imaging instrumentation and techniques as applied to diagnostic radiology and other biomedical applications. It includes recent advances in various biomedical imaging modalities, multi-modality imaging and molecular imaging. The course is taught by experts in the respective fields and provides a broad based knowledge of modern biomedical imaging to prepare students for graduate studies and research in biomedical imaging. Also, the course will offer tours and practical experience with modern biomedical imaging equipment in clinical and research settings. Recommended course background: EN.520.432 or EN.580.472
Prerequisites: Students may not have taken EN.580.473.
Instructor(s): B. Tsui
Area: Engineering.

EN.580.779. Systems Bioengineering III. 4.0 Credits.
Computational and theoretical systems biology at the cellular and molecular level. Topics include organizational patterns of biological networks; analysis of metabolic networks, gene regulatory networks, and signal transduction networks; inference of pathway structure; and behavior of cellular and molecular circuits. Recommended Course Background: EN.580.221 and EN.580.222 or Permission Required.
Instructor(s): J. Bader.

EN.580.781. Biomedical Engineering Seminar. 1.0 Credit.
Instructor(s): W. Grayson.
EN.580.788. Biomedical Photonics II. 3.0 Credits.
This course serves as the continuation of 580.678 (520.678), Biomedical Photonics I. It will cover the advanced topics on biomedical photonics, including, but not limited to, light scattering (Rayleigh and Mie scattering), photon diffusion, polarization (birefringence), fluorescence, lifetime measurements, confocal microscopy, optical coherence tomography, nonlinear microscopy, and super-resolution microscopy. Representative biomedical applications of some of these technologies will be integrated into the relevant chapters. A hand-on lab section (optional) for students to design and build an imaging instrument, space permitting.
Instructor(s): K. Yarema.

EN.580.801. Research in Biomedical Engineering. 3.0 - 10.0 Credits.
Graduate Students only
Instructor(s): X. Li.

EN.580.802. Research in Biomedical Engineering. 3.0 - 10.0 Credits.
Directed research for MSE and PhD students
Instructor(s): K. Yarema.

EN.580.821. Applied Research and Grant Methodology I. 3.0 Credits.
Students will select a laboratory to host their research rotation within the first two weeks (ideally, before the start of the term) and will participate in lab-related activities for a minimum of 12 hours a week; at least 6 hours a week is expected to involve "in person" interaction between the PI or other members of the sponsoring lab and the student. Activities will include attendance at lab meetings, preparation of a research proposal, and "hands on" experimental, computational, or modeling tasks: in addition, attendance at department research seminars and class meetings is required. Periodic reports on your research proposal/project and progress, as well providing feedback on your 'colleagues' projects and proposals will also be expected. A final research proposal (to be presented in the format of a NIH R21-type grant application) will provide evidence that a student is capable of carrying out advanced research by identifying a significant biomedical problem, developing innovative approaches to solve it, and then designing a relevant and implementable research plan.
Instructor(s): K. Yarema.

EN.580.822. Applied Research and Grant Methodology II. 3.0 Credits.
Students will participate in lab related activities for at least 12 hours a week. These activities will include attendance at lab meetings, preparation of a research proposal, and "hands on" experimental, computational, or modeling tasks. In addition, attendance at research seminars and class meetings is expected. Finally, periodic reports on your research project and progress, as well providing feedback on your 'colleagues' projects and proposals, will be required. Finally a research proposal essay (to be presented in the format of a NIH F31 or NSF equivalent) grant application will be required (it is expected that the application will be submitted to the funding agency for students interested in continuing their research career); it is anticipated that this proposal will include data generated by the student over the Fall, Inter session, or Spring term(s).
Prerequisites: EN.580.821.

EN.580.850. BME MSE Research Practicum. 6.0 Credits.
BME MSE Research Practicum For Thesis-Track Students
Instructor(s): K. Yarema.

Cross Listed Courses
General Engineering
EN.500.745. Seminar in Computational Sensing and Robotics. 1.0 Credit.
Seminar series in robotics. Topics include: Medical robotics, including computer-integrated surgical systems and image-guided intervention. Sensor based robotics, including computer vision and biomedical image analysis. Algorithmic robotics, robot control and machine learning. Autonomous robotics for monitoring, exploration and manipulation with applications in home, environmental (land, sea, space), and defense areas. Biorobotics and neuromechanics, including devices, algorithms and approaches to robotics inspired by principles in biomechanics and neuroscience. Human-machine systems, including haptic and visual feedback, human perception, cognition and decision making, and human-machine collaborative systems. Cross-listed Mechanical Engineering, Computer Science, Electrical and Computer Engineering, and Biomedical Engineering.
Instructor(s): L. Whitcomb; P. Kazanzides.

Electrical Computer Engineering
EN.520.315. Introduction to Information Processing of Sensory Signals. 3.0 Credits.
An introductory course to basic concepts of information processing of human communication signals (sounds, images) in living organisms and by machine. Recommended Course Background: EN.520.214 (or EN.580.222) or consent of the instructor.
Instructor(s): H. Hermansky
Area: Engineering.

EN.520.434. Modern Biomedical Imaging Instrumentation and Techniques. 3.0 Credits.
An intermediate biomedical imaging course covering modern biomedical imaging instrumentation and techniques as applied to diagnostic radiology and other biomedical applications. It includes recent advances in various biomedical imaging modalities, multi-modality imaging and molecular imaging. The course is team taught by experts in the respective fields and provides a broad based knowledge of modern biomedical imaging to prepare students for graduate studies and research in biomedical imaging. Also, the course will offer tours and practical experience with modern biomedical imaging equipments in clinical and research settings. Co-listed with EN.580.473
Prerequisites: Students may not have taken EN.520.634
Instructor(s): B. Tsui.

EN.520.445. Audio Signal Processing. 3.0 Credits.
This course gives a foundation in current audio and speech technologies, and covers techniques for sound processing by processing and pattern recognition, acoustics, auditory perception, speech production and synthesis, speech estimation. The course will explore applications of speech and audio processing in human computer interfaces such as speech recognition, speaker identification, coding schemes (e.g. MP3), music analysis, noise reduction. Students should have knowledge of Fourier analysis and signal processing.
Prerequisites: Students make take EN.520.445 or EN.520.645, but not both.
Instructor(s): M. Elhilali
Area: Engineering.
EN.520.601. Introduction to Linear Systems Theory. 3.0 Credits.
A beginning graduate course in multi-input multi-output, linear, time-invariant systems. Topics include state-space and input-output representations; solutions and their properties; multivariable poles and zeros; reachability, observability and minimal realizations; stability; system norms and their computation; linearization techniques. Recommended Course Background: Undergraduate courses in control systems and linear algebra.
Instructor(s): P. Iglesias.

EN.520.622. Principles of Complex Networked Systems. 3.0 Credits.
By employing fundamental concepts from diverse areas of research, such as statistics, signal processing, biophysics, biochemistry, cell biology, and epidemiology, this course introduces a multidisciplinary and rigorous approach to the modeling and computational analysis of complex interaction networks. Topics to be covered include: overview of complex nonlinear interaction networks and their applications, graph-theoretic representations of network topology and stoichiometry, stochastic modeling of dynamic processes on complex networks and master equations, Langevin, Poisson, Fokker-Plank, and moment closure approximations, exact and approximate Monte Carlo simulation techniques, time-scale separation approaches, deterministic and stochastic sensitivity analysis techniques, network thermodynamics, and reverse engineering approaches for inferring network models from data.
Instructor(s): J. Goutsias.

Mechanical Engineering

EN.530.410. Biomechanics of the Cell. 3.0 Credits.
Mechanical aspects of the cell are introduced using the concepts in continuum mechanics. Discussion of the role of proteins, membranes and cytoskeleton in cellular function and how to describe them using simple mathematical models.
Instructor(s): S. Sun
Area: Engineering, Natural Sciences.

EN.530.426. Biofluid Mechanics. 3.0 Credits.
Course will cover selected topics from physiological fluid dynamics, including respiratory flow patterns, blood flow and pulse propagation, aerodynamics of phonation and speech, rheology of blood flow in the microcirculation, aquatic animal propulsion, and animal flight.
Instructor(s): R. Mittal
Area: Engineering.

EN.530.448. Biosolid Mechanics. 3.0 Credits.
This class will introduce fundamental concepts of statics and solid mechanics and apply them to study the mechanical behavior bones, blood vessels, and connective tissues such as tendon and skin. Topics to be covered include concepts of small and large deformation, stress, constitutive relationships that relate the two, including elasticity, anisotropy, and viscoelasticity, and experimental methods. Recommended Course Background: AS.110.201 and AS.110.302, as well as a class in statics and mechanics
Area: Engineering.

Applied Mathematics Statistics

EN.553.450. Computational Molecular Medicine. 4.0 Credits.
Computational systems biology has emerged as the dominant framework for analyzing high-dimensional “omics” data in order to uncover the relationships among molecules, networks and disease. In particular, many of the core methodologies are based on statistical modeling, including machine learning, stochastic processes and statistical inference. We will cover the key aspects of this methodology, including measuring associations, testing multiple hypotheses, and learning predictors, Markov chains and graphical models. In addition, by studying recent important articles in cancer systems biology, we will illustrate how this approach enhances our ability to annotate genomes, discover molecular disease networks, detect disease, predict clinical outcomes, and characterize disease progression. Whereas a good foundation in probability and statistics is necessary, no prior exposure to molecular biology is required (although helpful).
Prerequisites: (EN.553.420 AND EN.553.430) OR equivalent courses in probability and statistics.
Instructor(s): J. Bader
Area: Engineering, Quantitative and Mathematical Sciences.

EN.553.650. Computational Molecular Medicine. 4.0 Credits.
Computational systems biology has emerged as the dominant framework for analyzing high-dimensional “omics” data in order to uncover the relationships among molecules, networks and disease. In particular, many of the core methodologies are based on statistical modeling, including machine learning, stochastic processes and statistical inference. We will cover the key aspects of this methodology, including measuring associations, testing multiple hypotheses, and learning predictors, Markov chains and graphical models. In addition, by studying recent important articles in cancer systems biology, we will illustrate how this approach enhances our ability to annotate genomes, discover molecular disease networks, detect disease, predict clinical outcomes, and characterize disease progression. Whereas a good foundation in probability and statistics is necessary, no prior exposure to molecular biology is required (although helpful).
Area: Engineering, Quantitative and Mathematical Sciences.

Computer Science

EN.601.350. Introduction to Genomic Research. 3.0 Credits.
This course will use a project-based approach to introduce undergraduates to research in computational biology and genomics. During the semester, students will take a series of large data sets, all derived from recent research, and learn all the computational steps required to convert raw data into a polished analysis. Data challenges might include the DNA sequences from a bacterial genome project, the RNA sequences from an experiment to measure gene expression, the DNA from a human microbiome sequencing experiment, and others. Topics may vary from year to year. In addition to computational data analysis, students will learn to do critical reading of the scientific literature by reading high-profile research papers that generated groundbreaking or controversial results. [Applications] Recommended Course Background: Knowledge of the Unix operating system and programming expertise in a language such as Perl or Python.
Instructor(s): S. Salzberg
Area: Engineering.
EN.601.448. Computational Genomics: Data Analysis. 3.0 Credits.
Genomic data has the potential to reveal causes of disease, novel drug
targets, and relationships among genes and pathways in our cells.
However, identifying meaningful patterns from high-dimensional genomic
data has required development of new computational tools. This course
will cover current approaches in computational analysis of genomic
data with a focus on statistical methods and machine learning. Topics
will include disease association, prediction tasks, clustering and
dimensionality reduction, data integration, and network reconstruction.
There will be some programming and a project component. [Applications]
Recommended Course Background: EN.601.226 or other programming
experience, probability and statistics, linear algebra or calculus. Students
may receive credit for EN.601.448 or EN.601.748, but not both.
Prerequisites: Students may receive credit for EN.601.448 or
EN.601.748, but not both.
Instructor(s): A. Battle
Area: Engineering.

EN.601.461. Computer Vision. 3.0 Credits.
This course gives an overview of fundamental methods in computer
vision from a computational perspective. Methods studied include:
camera systems and their modelling, computation of 3-D geometry from
binocular stereo, motion, and photometric stereo; and object recognition.
Edge detection and color perception are also covered. Elements of
machine vision and biological vision are also included. [Applications]
Prerequisites (soft): intro programming, linear algebra, and prob/stat.
Prerequisites: Students may only earn credit for one of the following:
EN.600.361, EN.600.461/EN.601.461, or EN.600.661/EN.601.661.
Students may not have taken EN.601.761
Instructor(s): A. Reiter
Area: Engineering, Quantitative and Mathematical Sciences.

EN.601.476. Machine Learning: Data to Models. 3.0 Credits.
How can robots localize themselves in an environment when navigating?
Can we predict which patients are at greatest-risk for complications in
the hospital? Which movie should I recommend to this user given his
history of likes? Many such big data questions can be answered using
the paradigm of probabilistic models in machine learning. These are
especially useful when common off-the-shelf algorithms such as support
vector machines and k-means fail. You will learn methods for clustering,
classification, structured prediction, recommendation and inference.
We will use Murphy’s book, Machine Learning: a Probabilistic Perspective,
as the text for this course. Assignments are solved in groups of size 1-3
students. The class will have 4 interactive sessions during which we
brainstorm how to solve example open-ended real-world problems with
the tools learnt in class. Students are also required to do a project of
their choice within which they experiment with the ideas learnt in class.
[Analysis or Applications] Students may receive credit for EN.601.476
or EN.601.776, but not both. Prerequisites include Intro Prob/Stat, Linear
Algebra and Intro Machine Learning as well as strong background in s.
Instructor(s): S. Saria
Area: Engineering, Quantitative and Mathematical Sciences.

EN.601.748. Computational Genomics: Data Analysis. 3.0 Credits.
Graduate level version of EN.601.448. [Applications] Recommended
Course Background: EN.601.226 or other programming experience,
probability and statistics, linear algebra or calculus. Students may receive
credit for EN.601.448 or EN.601.748 but not both.
Prerequisites: Students may receive credit for EN.601.448 or
EN.601.748, but not both.
Instructor(s): A. Battle
Area: Engineering.