BIOENGINEERING (BE)

BE 1000 Introduction to Bioengineering
Survey course introducing students to the breadth of bioengineering. Course consists of introductory lectures, guest speakers/panelists, and a series of small assignments that allow students to explore different facets of bioengineering and the Penn Bioengineering program.
Fall
0.5 Course Units

BE 2000 Introduction to Biomechanics
This course investigates the application of statics and strength of materials to soft and hard biologic tissues. The course will cover simple force analyses of the musculoskeletal system and introduces the fundamentals of the mechanics of materials including axial loading, torsion and bending and their application to biomechanics. The lecture and recitation will be complemented with hands-on examples emphasizing connections between theoretical principles and practical applications.
Fall
Prerequisite: MATH 1410 AND (PHYS 0140 OR PHYS 0150)
1 Course Unit

BE 2200 Biomaterials
This course investigates the application of materials science and engineering to biomedical applications, with a focus on polymers, ceramics, and metals. The course will cover concepts related to basic material fabrication and synthesis, structure and property characterization, as well as applications of biomaterials. The lecture and recitation will be complemented with laboratory examples of material assessment and characterization.
Spring
Prerequisite: BE 2000 AND CHEM 1022
1 Course Unit

BE 2700 Bioengineering Laboratory Principles
This course will cover a variety of bioengineering laboratory principles and techniques including data collection, analysis and reporting. Students will explore tools related to mechanics, materials and electronics with applications in the bioengineering field. Corequisite with BE 2200.
Spring
Prerequisite: BE 2000 AND (ENGR 1050 OR CIS 1200 OR CIS 1210)
1 Course Unit

BE 3010 Bioengineering Signals and Systems
Properties of signals and systems; Examples of biological and biomedical signal and systems; Signal operations, continuous and discrete signals; Linear, time invariant systems; Time domain analysis; Systems characterized by linear constant-coefficient differential equations; Fourier analysis with applications to biomedical signals and systems; Introduction to filtering; Sampling and the sampling theorem. Examples vary from year to year, but usually include signals such as the ECG and blood pressure wave, principles of signal coding in the auditory system and cochlear implants, and simple applications in biomedical imaging.
Fall or Spring
Prerequisite: (MATH 2400 OR ENM 2400) AND (PHYS 0141 OR PHYS 0151)
1 Course Unit

BE 3060 Cellular Engineering
The biological cell is a complex machine and its function is at the root of all physiology and many pathologies. Recent advances in molecular and cell biology enable the redesign of cell function. This course aims to develop a quantitative understanding of cell function, and how we might go about changing cell function through intelligent redesign. The course covers topics ranging from receptor binding and endocytosis, cell adhesion and motility, cell function in the immune system, systems and synthetic biology, genetic knockdown and manipulation using CRISPR and gene therapy, and strategies for immunotherapy including chimeric antigen receptor therapy (carT).
Fall
Prerequisite: CHEM 1022 AND (MATH 2400 OR ENM 2400) AND (PHYS 0140 OR PHYS 0150) AND (PHYS 0141 OR PHYS 0151) AND BIOL 1121 AND (ENGR 1050 OR CIS 1200 OR CIS 1210)
1 Course Unit

BE 3090 Bioengineering Modeling, Analysis and Design Laboratory I
BE 3090 is a one course-unit laboratory course with a focus on combining experimental and mathematical approaches to understand biological systems and solve bioengineering problems. The course content integrates concepts from mathematics, physics, signal analysis, control engineering , mass transport, and heat transfer with applications in physiology and pharmacology. Areas of emphasis are model development and validation, statistical analysis, experimental design, error analysis and uncertainty, and scientific writing.
Fall
Prerequisite: (ENGR 1050 OR CIS 1200 OR CIS 1210) AND (PHYS 0141 OR PHYS 0151) AND (MATH 2400 OR ENM 2400) AND BE 2000 AND BE 2200 AND BE 2700 AND (ENM 3750 OR ENGR 3440 OR STAT 4310)
1 Course Unit

BE 3100 Bioengineering Modeling, Analysis and Design Laboratory II
BE 3100 is a one course-unit laboratory course on the design of technology to measure and control biological systems. The course is divided into four modules: (i) microfluidics for point of care diagnostics, (ii) synthetic biology for predicting cellular behavior, (iii) electronics and signal analysis of bioelectrical signals, and (iv) bioanalytical spectroscopy for low-cost diagnostics. Each module will have two components: (i) a series of structured learning exercises to teach key concepts and methods of the topic that we are studying, and (ii) a design challenge, in which the understanding gained in the first component is used to design a solution to an open ended bioengineering challenge.
Spring
Prerequisite: (ENGR 1050 OR CIS 1200 OR CIS 1210) AND (PHYS 0141 OR PHYS 0151) AND (MATH 2400 OR ENM 2400) AND BE 2000 AND BE 2200 AND BE 2700 AND AND BE 3010 AND (ENM 3750 OR ENGR 3440 OR STAT 4310)
1 Course Unit

BE 3300 Self-Assembly of Soft Materials
Soft matter is found in diverse applications including sports (helmets & cloths); food (chocolate, egg); consumer products (e.g., lotions and shampoo); and devices (displays, electronics). Whereas solids and liquids are typically hard and crystalline or soft and fluid, respectively, soft matter can exhibit both solid and liquid like behavior. In this class, we investigate the thermodynamic and dynamic principles common to soft matter as well as soft (weak) forces, self-assembly and phase behavior. Classes of matter include colloidal particles, polymers, liquid crystalline molecules, amphiphilic molecules, biomacromolecules/membranes, and food.
Fall
Also Offered As: MSE 3300
Prerequisite: (MSE 2200 OR BE 2200) AND CHEM 1022 or equivalent
1 Course Unit

BE 3500 Introduction to Biotransport Processes
Introduction to basic principles of fluid mechanics and of energy and mass transport with emphasis on applications to living systems and biomedical devices.
Spring
Prerequisite: (MATH 2400 OR ENM 2400) AND (PHYS 0140 OR PHYS 0150) AND BE 2000
1 Course Unit

BE 4000 Preceptorship in Clinical Bioengineering
Introduction to the integration of biomedical engineering in clinical medicine through lectures and a preceptorship with clinical faculty. This course is for BE majors ONLY, with preference given to BSE students.
Spring
1 Course Unit

BE 4260 Immunology for Bioengineers
Immunology is fast growing field that is critical to human health and therapeutic development and engineering. To better prepare bioengineers for a career in immunotherapy and biotech areas, it is essential for them to learn the fundamental knowledge of the immune system and the diseases associated as well as common and emerging technologies used in immunological research. This will not only enable the students to communicate more effectively in a multidisciplinary team, it will also empower them to take advantage of their training in engineering and mathematics to develop tools to analyze the immune system with great depth, solve important questions in immunology, and engineering new therapeutics. Therefore, the goal of this course is to provide the immunology foundation for engineering students and technical background of commonly used tools and emerging technologies in immunological research. The course is open to upper level undergraduate students who have taken courses in biochemistry and/or cell biology.
Fall
Mutually Exclusive: BE 5260
1 Course Unit

BE 4700 Medical Devices
Lab-based course where students learn the fundamentals of medical device design through hands-on projects using microcontrollers. Students first learn basic design building blocks regularly employed in microcontroller-based medical devices, and then carry out a small design project using those building blocks. Projects are informed by reverse-engineering of competing products, FDA regulations, and marketplace considerations. Prerequisite: Junior or Senior BE Majors only. Students who have taken ESE 3500 or a similar course may not enroll. Permission of instructor required if course prerequisites not met.
Spring
1 Course Unit

BE 4720 Medical Device Development
Students will learn the process of developing medical devices that fulfill unmet patient needs. Students will be equipped with an understanding of what is required to lead a startup venture in medical devices including regulatory, legal, fundraising, team building and leadership. In lab, students will develop a proof-of-concept prototype device. Students will pitch their ideas to real med tech investors . The successful student will leave the class with the knowledge, skills and confidence to lead a startup venture in medical devices. If desired by the student, the proof-of-concept device can be used as the basis for their senior design project. Junior standing in Bioengineering or permission of the instructor if course prerequisite is not met.
Spring
1 Course Unit

BE 4800 Introduction to Biomedical Imaging
Introduction to the mathematical, physical and engineering design principles underlying modern medical imaging systems including x-ray computed tomography, ultrasonic imaging, and magnetic resonance imaging. Mathematical tools including Fourier analysis and the sampling theorem. The Radon transform and related transforms. Filtered backprojection and other reconstruction algorithms. Bloch equations, free induction decay, spin echoes and gradient echoes. Applications include one-dimensional Fourier magnetic resonance imaging, three-dimensional magnetic resonance imaging and slice excitation.
Spring
Prerequisite: BE 3010 OR ESE 3250
1 Course Unit

BE 4830 Physics of Medical/Molecular Imaging
This course will provide a comprehensive survey of modern medical imaging modalities and the emerging field of molecular imaging. The basic principles of X-ray, ultrasound, nuclear imaging, and magnetic resonance imaging will be reviewed. The course will also cover concepts related to contrast media and targeted molecular imaging. Topics to be covered include the chemistry and mechanisms of various contrast agents, approaches to identifying molecular markers of disease, ligand screening strategies, and the basic principles of toxicology and pharmacology relevant to imaging agents.
Fall
Mutually Exclusive: BE 5830
Prerequisite: MATH 2410
1 Course Unit

BE 4900 Independent Project in Bioengineering
An intensive independent study experience on an engineering or biological science problem related to bioengineering. Requires preparation of a proposal, literature evaluation, and preparation of a paper and presentation. Regular progress reports and meetings with faculty advisor are required. Sophomore, Junior and Senior BE majors only.
Fall or Spring
1 Course Unit

BE 4920 Independent Project in Bioengineering
Second semester of an independent project. Sophomore, Junior and Senior BE majors only.
Fall or Spring
1 Course Unit

BE 4950 Senior Design Project
Group design projects in various areas of bioengineering. Project ideas are proposed by the students in the Spring semester of the Junior year and refined during the Fall semester. The course guides the students through choosing and understanding an impactful biomedical problem, defining characteristics of a successful design solution to eliminate or mitigate a problem or fulfill a need, identifying and prioritizing constraints, creatively developing potential design solutions, iteratively refining design options, defining and implementing an optimal solution , and evaluating how well the solution fulfills the need. Final oral and written reports are required. Also emphasized are teamwork, project management, time management, regulations/standards, and effective communication. Seniors in BE or Department Permission.
Fall
1 Course Unit

BE 4960 Senior Design Project
Second semester of a two semester design project. Seniors in BE or Department Permission.
Spring
1 Course Unit

BE 4970 Senior Thesis in Biomedical Science
An intensive independent project experience incorporating both technical and non-technical aspects of the student's chosen career path. Chosen topic should incorporate elements from the student's career path electives, and may involve advisors for both technical and non-technical elements. Topics may range from biomedical research to societal, technological and business aspects of Bioengineering. A proposal, regular progress reports and meetings with a faculty advisor, a written thesis, and a presentation are required. Seniors in BAS or Department Permission.
Fall
1 Course Unit

BE 4980 Senior Thesis in Biomedical Science
Second semester of a year-long project. Seniors in BAS or Department Permission.
Spring
1 Course Unit

BE 5020 From Biomedical Science to the Marketplace
This course explores, through own work (this is, own discovery) the transition from fundamental knowledge to its ultimate application in a clinical device or drug. Emphasis is placed upon factors that influence this transition and upon the integrative requirements across many fields necessary to achieve commercial success. Special emphasis is placed upon entrepreneurial strategies, intellectual property, and the FDA process of proving safety and efficacy. Graduate students or permission of the instructor.
Fall
1 Course Unit

BE 5040 Biological Data Science II: Data Mining Principles for Epigenomics
This course will teach upper level undergraduates and graduate students how to answer biological questions by harnessing the wealth of genomic and epigenomic data sets generated by high-throughput sequencing technologies. Graduate students or permission of the instructor
Spring
1 Course Unit

BE 5060 Introduction to Neuroengineering
This graduate-level course offers a comprehensive introduction to the interdisciplinary field of neuroengineering, focusing on the integration of neuroscience and engineering principles to advance our understanding of the nervous system and develop innovative technologies for neural interfacing and control. Through in-class lectures and focused hands-on problems, students will learn the fundamentals of neurophysiology, as well as statistical analysis of neural signals. The course will also provide the students with an overview of non-electrical neural I/O modalities, such as neurophotonics, magnetic, mechanical, and chemical methods. By the end of the course, students will gain a deeper understanding of the state-of-the art methods used in modern system neuroscience, neuromodulation systems, neuroprosthetics, and brain-computer interfaces.
Fall
1 Course Unit

BE 5100 Biomechanics and Biotransport
The course is intended as an introduction to continuum mechanics in both solid and fluid media, with special emphasis on the application to biomedical engineering. Once basic principles are established, the course will cover more advanced concepts in biosolid mechanics that include computational mechanics and bio-constitutive theory. Applications of these advanced concepts to current research problems will be emphasized.
Spring
1 Course Unit

BE 5120 Bioengineering III: Biomaterials
This course provides a comprehensive background in biomaterials. It covers surface properties, mechanical behavior and tissue response of ceramics, polymers and metals used in the body. It also builds on this knowledge to address aspects of tissue engineering, particularly the substrate component of engineering tissue and organs. General Chemistry, basic biomechanics.
Fall
1 Course Unit

BE 5130 Human Centered Design for Clinical Emergency Medicine
This capstone course is a project-based experience for graduate students where they will effectively serve as design consultants for Penn Department of Emergency Medicine. Selected students should have familiarity of technical fundamentals, such as engineering design and data analysis, and will have the opportunity to use those skills to solve challenges facing two premier emergency departments. This flipped-classroom course combines lectures and significant asynchronous laboratory and clinical immersion experiences. By the end of the course, students will use human centered design to develop a functional prototype and collect preliminary data on their solution, which will be presented to Emergency Medicine Leadership.
Fall or Spring
1 Course Unit

BE 5140 Rehab Engineering and Design
Students will learn about problems faced by disabled persons and medical rehabilitation specialists, and how engineering design can be used to solve and ameliorate those problems. The course combines lectures, multiple design projects and exercises, and field trips to clinical rehabilitation facilities. Students will have substantial interaction with clinical faculty, as well as with patients. Prerequisite: Graduate students or permission of the instructor.
Fall
Also Offered As: IPD 5040
1 Course Unit

BE 5160 Introduction to High-Performance Scientific Computing
Research problems in the domain of physical, biological and biomedical sciences and engineering often span multiple time and length-scales from the molecular to the organ/organism, owing to the complexity of information transfer underlying biological mechanisms. Multiscale modeling (MSM) and high-performance scientific computing (HPC) have emerged as indispensable tools for tackling such complex problems. However, a paradigm shift in training is now necessary to leverage the rapid advances, and emerging paradigms in HPC --- GPU, cloud, exascale supercomputing, quantum computing --- that will define the 21st century. This course is a collaboration between Penn, UC Berkeley, and the Extreme Science and Engineering Discovery Environment (XSEDE) which administers several of the federally funded research purpose supercomputing centers in the US. It will be taught as a regular 1 CU course at Penn by adopting a flip-classroom/active learning format. The course is designed to teach students how to program parallel architectures to efficiently solve challenging problems in science and engineering, where very fast computers are required either to perform complex simulations or to analyze enormous datasets. The course is intended to be useful for students from many departments and with different backgrounds, e.g., scholar of Penn Institute for Computational Science, although we will assume reasonable programming skills in a conventional (non-parallel) language, as well as enough mathematical skills to understand the problems and algorithmic solutions presented.
Fall or Spring
Also Offered As: CBE 5060
1 Course Unit

BE 5180 Optical Microscopy
An introduction to the fundamental concepts of optics and microscopy. Geometrical optics: ray tracing, optical elements, imaging systems, optical aberrations. Physical optics: the electromagnetic spectrum, the wave equation, diffraction, interference and interferometers, optical resolution limits, optical coherence, lasers. Microscopy methods: phase contrast, differential interference contrast, fluorescence microscopy, confocal microscopy, multiphoton microscopy, optical coherence tomography, superresolution microscopy.
Fall
Prerequisite: MATH 2400
1 Course Unit

BE 5210 Brain-Computer Interfaces
The course is geared to advanced undergraduate and graduate students interested in understanding the basics of implantable neuro-devices, their design, practical implementation, approval, and use. Reading will cover the basics of neuro signals, recording, analysis, classification, modulation, and fundamental principles of Brain-Machine Interfaces. The course will be based upon twice weekly lectures and "hands-on" weekly assignments that teach basic signal recording, feature extraction, classification and practical implementation in clinical systems. Assignments will build incrementally toward constructing a complete, functional BMI system. Fundamental concepts in neurosignals, hardware and software will be reinforced by practical examples and in-depth study. Guest lecturers and demonstrations will supplement regular lectures. BE 3010 (Signals and Systems) or equivalent, computer programming experience, preferably MATLAB (e.g., as used the BE labs, BE 3100). Some basic neuroscience background (e.g. BIOL 2310, BE 3050, INSC core course), or independent study in neuroscience, is required. This requirement may be waived based upon practical experience on a case by case basis by the instructor.
Spring
Also Offered As: NGG 5210
1 Course Unit

BE 5260 Immunology for Bioengineers
Immunology is fast growing field that is critical to human health and therapeutic development and engineering. To better prepare bioengineers for a career in immunotherapy and biotech areas, it is essential for them to learn the fundamental knowledge of the immune system and the diseases associated as well as common and emerging technologies used in immunological research. This will not only enable the students to communicate more effectively in a multidisciplinary team, it will also empower them to take advantage of their training in engineering and mathematics to develop tools to analyze the immune system with great depth, solve important questions in immunology, and engineering new therapeutics. Therefore, the goal of this course is to provide the immunology foundation for engineering students and technical background of commonly used tools and emerging technologies in immunological research. The course is open to upper level undergraduate students who have taken courses in biochemistry and/or cell biology.
Fall
Mutually Exclusive: BE 4260
1 Course Unit

BE 5270 Immune Engineering
This course would target graduate students and upper level undergraduate students. This course introduces to students the concept of immune engineering that ranges from vaccine design to cancer immunotherapy and cutting edge tools recently developed in these areas. It is best suited for graduate students and upper level undergraduate students who have had cell biology and immunology. We will build on the topics covered in Immunology and explore deeper questions and applications in cancer immunotherapy, infection, and auto-immune diseases, and high-throughput immune profiling technologies. The course will use a combination of lectures, journal clubs, and a final project presentation that will be discussed mirroring NIH study section format. The course is open to graduate students and upper level undergraduate students who have taken courses in biochemistry and/or cell biology.
Fall or Spring
1 Course Unit

BE 5280 Applied Medical Innovation I
Applied Medical Innovation I: Bedside to Bench is a hands-on, project-based team design experience for graduate students, offered in partnership with the Center for Health, Devices, and Technology (Penn Health Tech). The course acts as an idea INCUBATOR for projects originating from unmet clinical needs, identified by clinical collaborators, industry sponsors, and Penn Health Tech partners. By the end of this course, students will understand all aspects of medical device design, innovation, and entrepreneurship, including the importance of a clear problem definition and stakeholder input, an introduction to engineering design principles, and how to navigate the complex pathway by which these products reach patients. The end point of the semester is a final pitch (outlining the need, the solution, and the business opportunity) and a functional prototype with initial proof of concept data. The course is open to all graduate and senior undergraduate students (pre-application required).
Fall
1 Course Unit

BE 5290 Applied Medical Innovation II
Applied Medical Innovation II: Bench to Bedside is a hands-on, interdisciplinary, project experience for graduate students, offered in partnership with the Center for Health, Devices, and Technology (Penn Health Tech). The course acts as device ACCELERATOR for projects originating from Applied Medical Innovation I and Penn Health Tech. Students partner with experienced technical teams (clinicians + engineers) to create a commercialization plan for real-world, cutting-edge medical technologies under development at Penn. Students work closely with their interdisciplinary team to identify and validate the clinical need, stakeholder requirements, and business case in order to de-risk the technology, increase commercial potential, and package the idea for follow-on investment. In the second half of the course, students will also gain exposure to medical technology entrepreneurship and investing. The course is open to all graduate and senior undergraduate students (pre-application required).
1 Course Unit

BE 5300 Theoretical and Computational Neuroscience
This course will develop theoretical and computational approaches to structural and functional organization in the brain. The course will cover: (i) the basic biophysics of neural responses, (ii) neural coding and decoding with an emphasis on sensory systems, (iii) approaches to the study of networks of neurons, (iv) models of adaptation, learning and memory, (v) models of decision making, and (vi) ideas that address why the brain is organized the way that it is. The course will be appropriate for advanced undergraduates and beginning graduate students. A knowledge of multi-variable calculus, linear algebra and differential equations is required (except by permission of the instructor). Prior exposure to neuroscience and/or Matlab programming will be helpful.
Spring
Also Offered As: NGG 5940, NRSC 5585, PHYS 5585, PSYC 5390
1 Course Unit

BE 5320 Computational Biophysics
This course targets graduate students and upper level undergraduates with a background in physical chemistry. Proteins and other biomolecules perform all of the active functions that we associate with life, from muscle contraction to sensing light and sound. Like the machines we are used to operating on macroscopic scales, these molecular machines have many moving parts that are essential to their function and dysfunction. This course introduces a framework for reasoning about such dynamics and computational tools for interrogating them.
Also Offered As: BBCB 5320, BMB 5320
1 Course Unit

BE 5370 Biomedical Image Analysis
This course covers the fundamentals of advanced quantitative image analysis that apply to all of the major and emerging modalities in biological/biomaterials imaging and in vivo biomedical imaging. While traditional image processing techniques will be discussed to provide context, the emphasis will be on cutting edge aspects of all areas of image analysis (including registration, segmentation, and high-dimensional statistical analysis). Significant coverage of state-of-the-art biomedical research and clinical applications will be incorporated to reinforce the theoretical basis of the analysis methods. Prerequisite: Mathematics through multivariate calculus (MATH 2410), programming experience, as well as some familiarity with linear algebra, basic physics, and statistics.
Fall or Spring
Also Offered As: CIS 5370, MPHY 6090
1 Course Unit

BE 5400 Principles of Molecular and Cellular Bioengineering
This course aims to provide theoretical and conceptual principles underlying biomolecular and biological systems. The course will start with basic and advanced concepts in physical chemistry and thermodynamics and introduce statistical mechanics as a tool to understand molecular interactions. The applications will be of relevance to bioengineering and biology disciplines. The course will not shy away from mathematical formulations and will stress the molecular perspective. This course explores physical biology of the cell across several length and timescales, while simultaneously emphasizing molecular specificity and clinical implications such as disease outcome or biomedical applications. The course emphasizes how the basic tools and insights of engineering, physics, chemistry, and mathematics can illuminate the study of molecular and cell biology to make predictive biomedical models and subject them to clinical validation. Drawing on key examples and seminal experiments from the current bioengineering literature, the course demonstrates how quantitative models can help refine our understanding of existing biological data and also be used to make useful clinical predictions. The course blends traditional models in cell biology with the quantitative approach typical in engineering, in order to introduce the student to both the possibilities and boundaries of the emerging field of physical systems biology. While teaching physical model building in cell biology through a practical, case-study approach, the course explores how quantitative modeling based on engineering principles can be used to build a more profound, intuitive understanding of cell biology. Worksheets will be integral to this course. Recitation will comprise of biweekly illustrations of problems and concepts from the worksheets and biweekly quizzes
Fall or Spring
Also Offered As: CBE 5400
1 Course Unit

BE 5440 Computational Science of Energy and Chemical Transformations
Our theoretical and computational capabilities have reached a point where we can do predictions of materials on the computer. This course will introduce students to fundamenta l concepts and techniques of atomic scale computational modeling. The material will cover electronic structure theory and chemical kinetics. Several well-chosen applications in energy and chemical transformations including study and prediction of properties of chemical systems (heterogeneous, molecular, and biological catalysts) and physical properties of materials will be considered.
This course will have modules that will include hands-on computer lab experience and teach the student how to perform electronic structure calculations of energetics which form the basis for the development of a kinetic model for a particular problem, which will be part of a project at the end of the course. Thermodynamics, Kinetics, Physical Chemistry, Quantum Mechanics. Undergraduates should consult and be given permission by the instructor.
Fall or Spring
Also Offered As: CBE 5440, MSE 5440
1 Course Unit

BE 5470 Fundamental Techniques of Imaging
This laboratory course covers the fundamentals of modern medical imaging techniques. Students will participate in a series of hands-on exercises, covering the principals of X-ray imaging, CT imaging, photoacoustic imaging, diffusion tensor imaging, localized magnetic resonance (MR) spectroscopy, MR contrast agents, diffuse optical spectroscopy, and bioluminescence imaging. Each lab is designed to reinforce and expand upon material taught in BE 4830/BE 5830 Molecular Imaging and MMP 5070 Physics of Medical Imaging. Graduate students or permission of the instructor.
Spring
1 Course Unit

BE 5500 Continuum Tissue Mechanics
This course introduces tensor calculus and continuum mechanics, with a focus on finite-deformation behavior of biological tissues including skin, tendon/ligament, cartilage, bone, blood vessels, nerves. Senior/Graduate Student in Bioengineering or permission of the instructor.
Spring
1 Course Unit

BE 5510 Biomicrofluidics
The focus of this course is on microfluidics for biomedical applications. Topics to be covered in the first half of this course include microscale phenomena, small-scale fabrication techniques, and sensing technologies that are often leveraged in the development of microfluidic systems for the study of biomolecules, cells, tissues, and organs in living biological systems. In the second half of this course, strong emphasis will be placed on the application of microfluidics in cell biology, bioanalytical chemistry, molecular biology, tissue engineering, and drug discovery. Prereqisite: Experience with an undergraduate level fluid mechanics course is preferred. Examples of relevant SEAS courses include BE 3500 (Biotransport), CBE 3500 (Fuild Mechanics), and MEAM 3020 Fluid Mechanics).
Fall
1 Course Unit

BE 5530 Principles, Methods, and Applications of Tissue Engineering
Tissue engineering demonstrates enormous potential for improving human health. This course explores principles of tissue engineering, drawing upon diverse fields such as developmental biology, cell biology, physiology, transport phenomena, material science, and polymer chemistry. Current and developing methods of tissue engineering, as well as specific applications will be discussed in the context of these principles. A significant component of the course will involve review of current literature within this developing field. Graduate Standing or instructor's permission.
Spring
1 Course Unit

BE 5550 Nanoscale Systems Biology
Nano-science and engineering approaches to systems in biology are of growing importance. They extend from novel methods, especially microscopies that invite innovation to mathematical and/or computational modeling which incorporates the physics and chemistry of small scale biology. Proteins and DNA, for example, are highly specialized polymers that interact, catalyze, stretch and bend, move, and/or store information. Membranes are also used extensively by cells to isolate, adhere, deform, and regulate reactions. In this course, students will become familiar with cell & molecular biology and nano-biotechnology through an emphasis on nano-methods, membranes, molecular machines, and 'polymers' - from the quantitative perspectives of thermodynamics, statistical physics, and mechanics. We specifically elaborate ideas of energetics, fluctuations and noise, force, kinetics, diffusion, etc. on the nano- thru micro- scale, drawing from very recent examples in the literature. Laboratory experiments will provide hands-on exposure to microscopies in a biological context (eg. fluorescence down to nano-scale, AFM), physical methods (eg. micromanipulation, tracking virus-scale particles or quantum dots), and numerical problems in applied biophysics, chemistry, and engineering. A key goal of the course is to familiarize students with the concepts and technology (plus their limitations) as being employed in current research problems in nanoscale systems biology, extending to nanobiotechnology. Prerequisite: Background in Biology, Physics, Chemistry or Engineering with coursework in Thermodynamics or permission of the instructor.
Fall
Also Offered As: CBE 5550, MEAM 5550
1 Course Unit

BE 5560 Molecular Diagnostics for Precision Medicine
This course provides a broad overview of current molecular diagnostics that have been implemented in clinical settings. Students will gain knowledge in the field and they will apply the knowledge to come up with their own ideas on next generation molecular diagnostics that can resolve currently intractable clinical problems. The course also introduces key concepts and emerging concepts in the area of diagnostics. Topics covered in this course include point-of-care diagnostics, microfluidics, microscopy, liquid biopsy, digital assays, microfabrication, molecular probe design, biomarkers, biosensing, commercialization, and machine learning based data analysis. Upon completion of the course, students will have the ability to design their own diagnostic platforms.
Fall
1 Course Unit

BE 5570 Quantitative Principles of Drug Design
An application of fundamental quantitative principles to biological problems across a wide range of scales. Through an engineering lens, we examine biology on the genetic, molecular, cellular, and population level. Using this information, we can begin to rationally engineer safe and effective biologics. Emphasis is placed on quantitative modeling in MATLAB/Python and immunotherapy design. Prerequisites: Pre-reqs for UG students ENM 2400 or Math 2400, BE 3090, BE 3100 or by permission of the instructor. Recommended: Introduction to Coding Course for MATLAB or Python at the level of ENGR 1050
1 Course Unit

BE 5580 Principles of Biological Fabrication
BE 558 introduces methodological approaches that are currently used for the de novo construction of biological molecules - primarily, nucleic acids and proteins - and how to use these molecules to engineer the properties of cells and intact tissue. By the end of the semester, students should (i) possess a molecular-scale understanding of key biological synthesis (ii) and assembly processes, (ii) gain an intuition for how to create novel (iii) methodologies based on these existing processes, and (iii) appreciate (iv) the drivers of technology adoption (e.g. cost, time, ease, and (v) reproducibility). Throughout the course, we will place the material in context of applications in bioengineering and human health, including: protein engineering, drug discovery, synthetic biology & optogenetics, bio-inspired materials, and bio-electronic devices. Graduate standing or permission of the instructor. Undergraduate level biology, physics and chemistry.
Fall, odd numbered years only
1 Course Unit

BE 5590 Multiscale Modeling of Chemical and Biological Systems
This course provides theoretical, conceptual, and hands-on modeling experience on three different length and time scales - (1) electronic structure (A, ps); (2) molecular mechanics (100A, ns); and (3) deterministic and stochastic approaches for microscale systems (um, sec). Students will gain hands-on experience, i.e., running codes on real applications together with the following theoretical formalisms: molecular dynamics, Monte Carlo, free energy methods, deterministic and stochastic modeling, multiscale modeling. Prerequisite: Undergraduate courses in numerical analysis and physical chemistry.
Not Offered Every Year
Also Offered As: CBE 5590, SCMP 5590
1 Course Unit

BE 5610 Musculoskeletal Biology and Bioengineering
The goal of this course is to educate students in core principles and expose them to cutting-edge research in musculoskeletal biology and bioengineering through (1) lectures covering the basic engineering principles, biological fundamentals, and clinical practices involved in the function, repair, and regeneration of the musculoskeletal tissues; (2) critical review and presentation by student groups of recent and seminal publications in the field related to the basic science, translation, and clinical practice of musculoskeletal biology and bioengineering, with discussion input by faculty members with relevant expertise. This course will place an emphasis on delivering multidisciplinary knowledge of cell and molecular biology, mechanics, material science, imaging, and clinical medicine as it relates to the field of musculoskeletal bioengineering and science. Graduate student standing in Engineering and/or CAMB. Undergraduate students with permission of the instructor.
Fall, odd numbered years only
1 Course Unit

BE 5620 Drug Discovery and Development
Intro to Drug Discovery; Overview of Pharmaceutical Industry and Drug Development Costs, Timelines; High Throughput Screening (HTS): Assay Design and Sensitivity Solid Phase Synthesis and Combinatorial Chemistry; Enzyme Kinetics; Fluorescence, Linearity, Inner-filter effect, quenching; Time dynamics of a Michaelis-Menton Reaction; Competitive Inhibitor; FLINT, FRET, TRF, FP, SPA, alpha-screen; Enzyme HTS (protease); Cell based screening; Fura-2 ratio, loading signaling; Gfpcalmodulin-gfp integrated calcium response; Estrogen/ERE-Luc HTS; Problems with cell based screening (toxicity, permeability, nonspecificity); Instrumentation, Robotics/Automation; Z-factor; SAR, Positioning Scanning; Microarray HTS; IC50, % Conversion in HTS and IC50, Assay Optimization.
Fall
Also Offered As: CBE 5620
1 Course Unit

BE 5630 Advanced Topics in Musculoskeletal Biology & Bioengineering
This course is designed to build on core principles from BE5610 and will expose students to cutting-edge research in musculoskeletal engineering and science through (1) short lectures on key concepts and assays followed by (2) critical review and presentation by student groups of recent publications in the field, with discussion input by faculty members with relevant expertise. The course will prepare students for advanced doctoral studies in the field of musculoskeletal biology and bioengineering.
Spring, odd numbered years only
Prerequisite: BE 5610
1 Course Unit

BE 5650 Developmental Engineering of Tissues
This course discusses systems biology approaches to understanding tissue development, homeostasis, and organogenesis. Emphasis is placed on modern technologies, models, and approaches to understanding collective cell behaviors that sculpt tissue form and function, placing developmental principles within an engineering framework. We will consider morphogenetic, mechanobiology, and micro-engineering/sensing analyses. Senior Standing in Bioengineering or permission of the instructor. In keeping with modern graduate-level engineering classes, this course will assume some basic knowledge of coding and/or willingness to learn coding practices. The course will not attempt to serve as a comprehensive introduction to developmental biology (CAMB 5110: Principles of Development is a recommended potential companion course). However, your success in the course will not require familiarity with developmental biology.
Fall
1 Course Unit

BE 5660 Networked Neuroscience
The human brain produces complex functions using a range of system components over varying temporal and spatial scales. These components are couples together by heterogeneous interactions, forming an intricate information-processing network. In this course, we will cover the use of network science in understanding such large-scale and neuronal-level brain circuitry. Prerequisite: Graduate standing or permission of the instructor. Experience with Linear Algebra and MATLAB.
Spring
Also Offered As: ESE 5660
1 Course Unit

BE 5690 Systems Biology of Cell Signaling Behavior
This course discusses the principles of cell signaling and cell decisions. We start from a molecular description of cell signaling components. The course builds towards understanding how their interactions govern cell and tissue behavior and how these processes can breakdown in disease. We conclude with a survey of modern approaches to analyze and manipulate signaling networks to study and control biological systems. Graduate, Junior or Senior standing in Bioengineering or permission of the instructor.
Spring
1 Course Unit

BE 5700 Biomechatronics
Mechatronics is the combination of mechanical, electrical and computer engineering principles in the design of electromechanical systems. Biomechatronics is the application of these principles to human biology and includes orthopaedic, hearing, respiratory, vision and cardiovascular applications. In this hands-on, project-based course, these biomechatronic systems will be explored. Students will learn the basic mechanical and electrical elements needed to complete a biomechatronic design challenge including basic circuits, design considerations, material fabrication, microcontrollers and mechanisms (e.g. converting rotational motion into linear motion). Students will carry out a final design project utilizing these building blocks. A first course in programming (Matlab and/or C++ preferred) , Senior standing in BE or permission of the instructor
Fall
1 Course Unit

BE 5710 The Goals of Scientific Inquiry
A key skill needed for a successful career in engineering and applied science is the ability to capitalize on current advances in technology (e.g., big data, data science, machine learning) to solve important problems. To gain this ability a student must go beyond an understanding of the technology itself, and instead must achieve the more challenging capacity to identify tractable problems, to formulate good questions, to initiate big ideas, to guide the advancement of science. In this course, we provide a broad and rich perspective on science as a field, laying the critical groundwork for just such achievements. Prerequisites: The course is open to all graduate students. Undergraduates must have passed Math 2410, ENM 3750 or equivalent, CIS 1200 or higher, and PHYS 0141. PHIL 1800 or similar is beneficial but not required.
Spring, even numbered years only
1 Course Unit

BE 5730 Soft Skills for Bioengineering PhDs
This is a required course for BE PhD candidates and covers topics related to bioengineering and the PhD level graduate studies. The goal is to expose students to a breadth of bioengineering topics beyond their specific dissertation work.
Fall or Spring
0.5 Course Units

BE 5740 Special Topics in Bioengineering
This special topics course will focus on emerging topics in Bioengineering at the macroscale from organ to population level covering genomics, epigenetics, molecular and cellular systems with focus on immunology, cancer, neuroengineering, biomechanics, and other facets of bioengineering. This course is intended for PhD students in their first year of study.
Spring
1 Course Unit

BE 5760 The Cell as a Machine
The course is a general survey of cell mechanics, emphasizing problem-based and hypothesis-testing approaches. It is based on the concept that the cell is a complex machine, and that the cell can therefore be understood by first understanding principles of complex functions in robust machines, and then understanding the design and operation of complex functions specifically in cells. The course has been offered internationally for many years using a reverse-classroom format. Lectures, which are given primarily by Michael Sheetz, former director of the Mechanobiology Institute at the National University of Singapore, are pre-recorded and viewed independently by students, who also do outside reading and prepare questions in advance of a live, remote, 2 hour question/discussion session with Dr. Sheetz. The Penn course directors are present at all question/discussion sections, and lead tutorials on site. Homework and exams are graded, and Penn course directors will review them for consistency. Other sites that will be involved in the course in the coming year include Columbia, MIT, and Berkeley. Graduate Standing or permission of the instructor.
Fall
1 Course Unit

BE 5780 Principles of Controlled Release Systems
This course provides a basic understanding of the engineering of controlled release systems specifically geared towards the development of formulations for drug delivery, which stands as a 114 billion dollar industry. The course focuses on topics at the interface between engineering and medicine, such as biomaterials, pharmacokinetics, polymer chemistry, reaction kinetics, and transport phenomena. Design of controlled release systems for transdermal, aerosol, oral, gene, and targeted cellular delivery are discussed with emphasis placed on fabrication, US FDA regulatory considerations, and the relevant physiological milieu. The course comprises (1) foundational lectures that provide the basic tools for the student to elaborate a controlled delivery system, (2) an overview of key current research on biomedical controlled release systems for different pathologies and body compartments, (3) an elevator pitch competition for original ideas that use controlled release systems, and (4) a project; plan and presentation to implement the pitched controlled release; system idea to practice design and problem-solving skills and practice basic elements of business proposal. Graduate students and senior standing in Bioengineering, Chemical and Biomolecular Engineering, or permission of the instructor.
Fall
1 Course Unit

BE 5810 Techniques of Magnetic Resonance Imaging
Detailed introduction to the physics and engineering of magnetic resonance imaging as applied to medical diagnosis. Covered are magnetism spatial encoding principles, Fourier analysis, spin relaxation, imaging pulse sequences and pulse design, contrast mechanisms, chemical shift, flow encoding, diffusion and perfusion, and a discussion of the most relevant clinical applications.
Also Offered As: BMB 5810
1 Course Unit

BE 5830 Physics of Medical / Molecular Imaging
Physical principles of diagnostic radiology, fluoroscopy, computed tomography; principles of ultrasound and magnetic resonance imaging; radioisotope production, gamma cameras, SPECT systems, PET systems; diagnostic and nuclear medicine facilities and regulations. The course includes a component emphasizing the emerging field of molecular imaging.
Fall
Mutually Exclusive: BE 4830
1 Course Unit

BE 5840 The Mathematics of Medical Imaging and Measurement
The last several decades have seen major revolutions in both medical and non-medical and imaging technologies. Underlying all of these advances are sophisticated mathematical tools to model the measurement process and reconstruct images. This course begins with an introduction of the mathematical models and then proceeds to discuss the integral transforms that underlie these models: the Fourier transform, the Radon transform and the Laplace transform. We discuss how each of these transforms is inverted, both in theory and in practice. Along the way we study interpolation, sampling, approximation theory, filtering and noise analysis. This course assumes a thorough knowledge of linear algebra and a knowledge of analysis at the undergraduate level (MATH 3140 and MATH 3600 and MATH 3610, or MATH 5080 and MATH 5090).
Not Offered Every Year
Also Offered As: AMCS 5840, MATH 5840
Prerequisite: MATH 1410 AND (MATH 3600 OR MATH 5080) AND (MATH 3610 OR MATH 5090)
1 Course Unit

BE 5850 Materials for Bioelectronics
Bioelectronics is an emerging field that involves the use of engineering principles to create devices for applications in biology, medicine, and health sciences. One of the most important aspects of bioelectronics is the development of communication interfaces between biological materials (cells, tissues and organs) and manmade devices for optimal energy delivery and signal transduction efficacies. Progress in materials science and engineering is bringing revolutionary advances to the biointerface design and has unlocked unprecedented applications in various biomedical fields. This course focuses on the materials science and engineering concepts that are of relevance to bioelectronics. It also introduces basic biochemical, biophysical and physiological principles that are required to understand the design and application of bioelectronic devices.
Spring
Also Offered As: MSE 5850
1 Course Unit

BE 5990 Master's Independent Study
The purpose of BE 5990 is to allow a student to create a customized curriculum to study material beyond or outside the scope of our standard BE course offerings. Independent study is NOT a research or design project, it is a one-on-one or small-group course with a professor. The course should require an effort comparable to that of a regular course, about 10-12 hours per week. A paper or presentation is required.
Fall or Spring
1-4 Course Units

BE 6080 Medical Entrepreneurship: Commercializing Translational Science
This course provides in depth insight into the process by which health technology platforms including scientific discoveries are transformed into viable commercial entities. This includes methods to evaluate market opportunities and derisk critical assumptions within the rapidly changing academic and healthcare environment. Topics include intellectual property creation and licensing, technology transfer, regulatory pathways, raising capital/NIH SBIR/STTR grant funding, go to market strategy, market sizing, formation equity, and recruiting co-founders. The major project will involve the formation of teams that will create a defendable business plan and consummate in a presentation (pitch deck) intended to raise capital. The course will be especially valuable for students who may be considering entrepreneurial career paths including starting a company, working for an early stage venture, healthcare consulting, or assuming innovation leadership roles.
Spring
Also Offered As: MTR 6200
1 Course Unit

BE 6100 Special Topics - NeuroAI - A Principled Understanding of the Human Brain
Traditional neuroscience courses present a fragmented view of the field, cataloging empirical observations and theoretical constructs without providing strong conceptual links between them. The discipline has yet to establish core principles that promise an overarching understanding. This course, heavily leaning on deep learning, will provide such an overarching way of thinking about brains. The classes will mostly be lecture based, building on an upcoming textbook. Homework will primarily be the coding up and analyzing of models.
Fall or Spring
1 Course Unit

BE 6400 Mechanobiology of the Cell and its Microenvironment
This course is geared towards first and second-year graduate students in BGS/CAMB and SEAS/BE with an interest in the interface of extracellular matrix (ECM) cell biology and biomechanics. Students will learn about the ECM and adhesion receptors and their impact on the cytoskeleton and signaling, as well as fundamental concepts in biomechanics and engineered materials. We will discuss how these topics can inform the study of cell biology, physiology, and disease. An additional objective of the course is to give students experience in leading critical discussions and writing manuscript reviews. Invited outside speakers will complement the strengths of the Penn faculty. Offered in the spring semester of even years only.
Spring, even numbered years only
Also Offered As: CAMB 7030
Prerequisite: BIOM 6000
1 Course Unit

BE 6500 Advanced Biomedical Imaging Applications
The course will cover a broad range of biomedical imaging technologies including X-ray, MRI, US, molecular and optical imaging. The curriculum will focus on the design of biomedical imaging based research studies spanning from basic technology development through clinical trials. This discussion oriented course is expected prepare students for integrating imaging technology and biomedical concepts to answer biological and medical questions.
Fall
1 Course Unit

BE 6620 Advanced Molecular Thermodynamics
This course begins with a brief review of classical thermodynamics, including the development of Maxwell relationships and stability analysis. The remainder of the course develops the fundamental framework of statistical mechanics, then reviews various related topics including ideal and interacting gases, Einstein and Debye models of crystals, lattice models of liquids, and the basis of distribution function theory.
Fall
Also Offered As: CBE 6180, MEAM 6620
1 Course Unit

BE 6990 Bioengineering Graduate Seminar
This is a required course for BE PhD candidates and covers topics related to bioengineering and the PhD level graduate studies. The goal is to expose students to a breadth of bioengineering topics beyond their specific dissertation work.
Fall or Spring
0 Course Units

BE 7110 Integrative plant and animal mechanobiology
This course aims to provide students with an understanding of biomechanics that spans the plant and animal kingdoms, with the goal of emphasizing principles common to both. Major concepts include 1) Plant and Animal Cell Biology; 2) Solid, Fluid, and Transport Mechanics; and 3) Integrating Biology and Mechanics - Big Questions. In addition to lectures, there will be two journal article discussion sections. Most lectures will be given by Penn faculty, although selected topics (particularly in plant biology and mechanics) will be covered by faculty at other sites through lectures broadcast remotely. The Penn director will be present at all sessions of the class. Undergraduates require special permission from the director.
Fall
Also Offered As: CAMB 7110
1 Course Unit

BE 9950 Doctoral Dissertation Status
Ph.D. Students register for Doctoral Dissertation Status after they have advanced to Ph.D. candidacy by completing the Candidacy Exam which consists of the Dissertation Proposal Defense.. Permission required. For PhD candidates only.
Fall or Spring
0 Course Units

BE 9990 Master's Thesis
For students working on an advanced research program leading to the completion of master's thesis requirements.
Fall or Spring
1,2 Course Units

BE 9999 Independent Study Research
For Bioengineering doctoral students studying a specific advanced subject area. Students should discuss with the faculty supervisor the scope of the independent study/research and know the expectations and work involved.
Fall, Spring, and Summer Terms
1-3 Course Units