**BIOENGINEERING (BE)**

**BE 100 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. Course usually offered in fall term
Corequisite: MATH 104 AND PHYS 140
Activity: Lecture
0.5 Course Units
Notes: Freshmen only

**BE 200 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.
Course usually offered in fall term
Prerequisite: MATH 114 OR PHYS 140 OR PHYS 150
Corequisite: MATH 240
Activity: Lecture
1.0 Course Unit

**BE 220 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.
Course usually offered in spring term
Prerequisites: BE 200, CHEM 102
Activity: Lecture
1.0 Course Unit

**BE 225 Technology and Engineering in Medicine**
The course is appropriate for engineering and natural science majors including premeds. The prerequisites will not be waived. This course will provide an examination of technology with emphasis on engineering design and its impact on medicine and health. Planned topics change from year to year and include, for example, cochlear implants and visual sensory rehabilitative devices. The course includes homework and reading assignments. Every student presents a paper on a relevant biomedical technology and the underlying science and engineering design.
One-term course offered either term
Prerequisites: MATH 114, PHYS 140 and 141 or PHYS 150 and 151 or PHYS 170 and 171
Activity: Seminar
1.0 Course Unit

**BE 270 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.
Taught by: Dourte/Burdick
Course usually offered in spring term
Activity: Laboratory
1.0 Course Unit

**BE 301 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.
One-term course offered either term
Prerequisites: MATH 241, PHYS 141 OR 151, ENGR 105
Activity: Lecture
1.0 Course Unit

**BE 305 Engineering Principles of Human Physiology**
This course presents a quantitative, biophysical approach to physiology, focusing on the nervous, cardiovascular, and pulmonary systems. We will also emphasize computational modeling and analysis of physiological systems.
Course usually offered in spring term
Prerequisite: MATH 240 AND ENGR 105
Activity: Lecture
1.0 Course Unit

**BE 306 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).
Taught by: Hammer
Course usually offered in fall term
Prerequisites: CHEM 102, MATH 241, PHYS 140, 141, BIOL 121
Activity: Lecture
1.0 Course Unit
**BE 309 Bioengineering Modeling, Analysis and Design Laboratory I**

BE 309 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.

Course usually offered in fall term
Prerequisites: ENGR 105, PHYS 141, 151, MATH 240, BE 200, 220, ENM 375
Activity: Lecture
1.0 Course Unit

**BE 310 Bioengineering Modeling, Analysis and Design Laboratory II**

BE 310 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.

Course usually offered in spring term
Prerequisites: ENGR 105, PHYS 141, 151, BE 220, BIOL 121, 123, MATH 240, ENM 375
Corequisite: MATH 241 AND BE 301
Activity: Laboratory
1.0 Course Unit

**BE 330 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. Active learning activities will be included.

Course usually offered in fall term
Also Offered As: MSE 330
Prerequisite: CHEM 102 OR MSE 220 OR BE 220
Activity: Lecture
1.0 Course Unit

**BE 350 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.

Course usually offered in spring term
Prerequisites: MATH 240, PHYS 140 or 150, BE 200
Activity: Lecture
1.0 Course Unit

**BE 400 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.

Course usually offered in spring term
Activity: Lecture
1.0 Course Unit
Notes: Junior and Senior BE majors only

**BE 470 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 350 or a similar course may not enroll. Permission of instructor required if course prerequisites not met.

Course usually offered in spring term
Activity: Laboratory
1.0 Course Unit

**BE 472 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.

Course usually offered in spring term
Activity: Laboratory
1.0 Course Unit

**BE 470 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 350 or a similar course may not enroll. Permission of instructor required if course prerequisites not met.

Course usually offered in spring term
Activity: Laboratory
1.0 Course Unit

**BE 480 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.

Course usually offered in spring term
Prerequisite: BE 301 OR ESE 325
Activity: Lecture
1.0 Course Unit
BE 493 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. Course usually offered in fall term Also Offered As: BE 583, MPHY 602 Prerequisite: MATH 241 OR BIOL 215 OR BE 305 Activity: Lecture 1.0 Course Unit

BE 490 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. One-term course offered either term Prerequisites: Sophomore, Junior and Senior BE majors only Activity: Independent Study 1.0 Course Unit

BE 492 Independent Project in Bioengineering
Second semester of an independent project. One-term course offered either term Prerequisites: Sophomore, Junior and Senior BE majors only Activity: Independent Study 1.0 Course Unit

BE 495 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. Course usually offered in fall term Prerequisite: Seniors in BE or Department Permission Activity: Lecture 1.0 Course Unit

BE 496 Senior Design Project
Second semester of a two semester design project. Course usually offered in spring term Prerequisite: Seniors in BE or Department Permission Activity: Lecture 1.0 Course Unit

BE 497 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. Course usually offered in fall term Prerequisites: Seniors in BAS or Department Permission Activity: Lecture 1.0 Course Unit

BE 498 Senior Thesis in Biomedical Science
Second semester of a year-long project. Course usually offered in spring term Prerequisite: Seniors in BAS or Department Permission Activity: Lecture 1.0 Course Unit

BE 502 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. Course usually offered in fall term Prerequisite: Graduate students or permission of the instructor Activity: Lecture 1.0 Course Unit

BE 504 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. Course usually offered in spring term Prerequisites: Graduate students or permission of the instructor Activity: Lecture 1.0 Course Unit

BE 510 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. Course usually offered in spring term Prerequisites: MATH 241, BE 200, 350 Activity: Lecture 1.0 Course Unit
BE 512 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.
Course usually offered in fall term
Prerequisites: General Chemistry, basic biomechanics
Activity: Lecture
1.0 Course Unit

BE 514 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.
Course usually offered in fall term
Also Offered As: IPD 504
Activity: Lecture
1.0 Course Unit

BE 515 Bioengineering Case Studies
This course has the unofficial title "What Makes Medical Technology Work?" We will examine biomedical devices and technologies with significant engineering components for use in breast cancer detection, for minimally invasive treatment of cancer and other disease, and applied neuroscience technologies for rehabilitation. Various factors that determine the success of particular medical systems will be discussed, including the "fit" of the technology with a medical need, testing for safety and efficacy, FDA premarket approval requirements, clinical studies used to assess the technology for evidence-based medicine. The class will examine successful and unsuccessful examples of these technologies. The course will require extensive reading of papers from the professional literature, group presentations and papers. BE seniors and graduate students are encouraged to enroll.
Course usually offered in fall term
Prerequisites: Graduate students or permission of the instructor.
Activity: Lecture
1.0 Course Unit

BE 516 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.
Taught by: Ravi Radhakrishnan
One-term course offered either term
Activity: Lecture
1.0 Course Unit

BE 518 Optical Microscopy
Course usually offered in fall term
Prerequisite: MATH 240
Activity: Lecture
1.0 Course Unit
BE 521 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.
Course usually offered in spring term
Also Offered As: NGG 521
Prerequisites: BE 301 (Signals and Systems) or equivalent, computer programming experience, preferably MATLAB (e.g., as used the BE labs, BE 310). Some basic neuroscience background (e.g. BIOL 215, BE 305, 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.
Activity: Lecture
1.0 Course Unit

BE 530 Theoretical 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.
Taught by: Vijay Balasubramanian
Course usually offered in spring term
Also Offered As: BIBB 585, NGG 594, PHYS 585, PSYC 539
Prerequisites: Knowledge of multivariable 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.
Activity: Lecture
1.0 Course Unit

BE 537 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 241), programming experience, as well as some familiarity with linear algebra, basic physics, and statistics.
One-term course offered either term
Also Offered As: CIS 537
Activity: Lecture
1.0 Course Unit

BE 540 Biomolecular and Cellular Engineering
This course will introduce concepts and methods for the quantitative understanding of molecular and cellular phenomena. Topics include molecular recognition, receptor-ligand binding, viral infection, signal transduction, cell adhesion, motility, and cytoskeletal dynamics. The course requires mathematics at the level of differential equations, and some knowledge of Matlab programming. A basic knowledge of cell biology is suggested, although not required.
One-term course offered either term
Also Offered As: CBE 540
Activity: Lecture
1.0 Course Unit

BE 541 Engineering and Biological Principles in Cancer
This course provides an integrative framework and provides a quantitative foundation for understanding molecular and cellular mechanisms in cancer. The topics are divided into three classes: (1) the biological basis of cancer; (2) cancer systems biology; and (3) multiscale cancer modeling. Emphasis is placed on quantitative models and paradigms and on integrating bioengineering principles with cancer biology. Prerequisite: Seniors in BE or permission of the instructor.
Course usually offered in spring term
Also Offered As: CBE 541
Activity: Lecture
1.0 Course Unit

BE 546 Fundamental Techniques of Imaging I
This course covers the fundamentals of modern techniques in biological and in vivo biomedical imaging. This practical course consists of a series of hands-on lab exercises, covering major imaging modalities, but also extends to non-radiology modalities of interest in biological, pathological or animal imaging (e.g., optical imaging). Topics include x-ray, mammography, CT, proton therapy, radiation safety and brachytherapy. The emphasis will be on hands-on aspects of all areas of imaging and imaging analysis. Small groups of students will be led by a faculty member with technical assistance as appropriate.
Course usually offered in spring term
Prerequisites: Graduate students or permission of the instructor.
Activity: Lecture
1.0 Course Unit

BE 547 Fundamental Techniques of Imaging 2 (BE 483/583 or MMP 507 preferred).
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 BE483/583 Molecular Imaging and MMP507 Physics of Medical Imaging
Course usually offered in spring term
Prerequisites: Graduate students or permission of the instructor.
Activity: Lecture
1.0 Course Unit
**BE 550 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.
Course usually offered in spring term
Prerequisite: Senior/Graduate Student in Bioengineering or permission of the instructor
Activity: Lecture
1.0 Course Unit

**BE 551 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. Prerequisite: Experience with an undergraduate level fluid mechanics course is preferred. Examples of relevant SEAS courses include BE 350 (Biotransport), CBE 350 (Fluid Mechanics), and MEAM 302 Fluid Mechanics.
Course usually offered in fall term
Activity: Lecture
1.0 Course Unit

**BE 553 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.
Course usually offered in spring term
Prerequisite: Graduate Standing or instructor's permission
Activity: Lecture
1.0 Course Unit

**BE 554 Engineering Biotechnology**
Advanced study of re DNA techniques; bioreactor design for bacteria, mammalian and insect culture; separation methods; chromatography; drug and cell delivery systems; gene therapy; and diagnostics.
Course usually offered in spring term
Also Offered As: CBE 554
Activity: Lecture
1.0 Course Unit

**BE 555 Nanoscale Systems Biology**
Nanoscience 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 nanobiotechnology 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. Taught by: Discher
Course usually offered in fall term
Also Offered As: CBE 555, MEAM 555
Activity: Lecture
1.0 Course Unit
**BE 559 Multiscale Modeling of Chemical Systems**
This course provides theoretical, conceptual, and hands-on modeling experience on three different length and time scales: (1) electronic structure (Å, 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. Prerequisite: Undergraduate courses in numerical analysis and statistical mechanics. Course not offered every year
Also Offered As: CBE 559, SCMP 559
Activity: Lecture
1.0 Course Unit

**BE 561 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.
Course offered fall; odd-numbered years
Prerequisites: Graduate student standing in Engineering and/or CAMB. Undergraduate students with permission of the instructor.
Activity: Lecture
1.0 Course Unit

**BE 562 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 Solided 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; GFP calmodulin-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.
Course usually offered in fall term
Also Offered As: CBE 562
Activity: Lecture
1.0 Course Unit

**BE 565 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.
Course usually offered in fall term
Prerequisite: Senior Standing in Bioengineering or permission of the instructor
Activity: Lecture
1.0 Course Unit

**BE 566 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.
Course usually offered in spring term
Also Offered As: ESE 566
Activity: Lecture
1.0 Course Unit

**BE 567 Mathematical Computation Methods for Modeling Biological Systems**
This course will cover topics in systems biology at the molecular/cellular scale. The emphasis will be on quantitative aspects of molecular biology, with possible subjects including probabilistic aspects of DNA replication, transcription, translation, as well as gene regulatory networks and signaling. The class will involve analyzing and simulating models of biological behavior using MATLAB. Prerequisite: Graduate standing or permission of the instructor.
One-term course offered either term
Also Offered As: AMCS 567, GCB 567
Activity: Lecture
1.0 Course Unit

**BE 568 Causality for Medicine and Biology**
The goal of this course is to introduce students to the analysis of data which aims at understanding causal relations. Within biomedical research there are randomized experiments that effortlessly get at certain kinds of causality but generally only allow low-dimensional probing. There are also observational studies that generally do not meaningfully get at causality. The field of econometrics has worked out a great deal of approaches that meaningfully allow the estimation of causality without randomized experiments. This set of techniques is largely unknown in much of biology and medicine. We will thus review the econometric approaches with an eye towards applications to biology and medical problems. We will also review ways of infusing these techniques with machine learning approaches to obtain more meaningful estimates.
One-term course offered either term
Activity: Lecture
1.0 Course Unit
BE 569 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.
Course usually offered in spring term
Prerequisites: Graduate, Junior or Senior standing in Bioengineering or permission of the instructor
Activity: Lecture
1.0 Course Unit

BE 570 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.
Course usually offered in fall term
Prerequisites: A first course in programming (Matlab and/or C++ preferred), Senior standing in BE or permission of the instructor
Activity: Lecture
1.0 Course Unit

BE 571 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 241, ENME 375 or equivalent, CIS 120 or higher, and PHYS 141. PHIIL 025 or similar is beneficial but not required.
Taught by: Bassett, D
Course offered spring; even-numbered years
Activity: Lecture
1.0 Course Unit

BE 572 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.
Course usually offered in fall term
Prerequisites: Graduate standing in Bioengineering, Chemical and Biomolecular Engineering, or permission of the instructor
Activity: Lecture
1.0 Course Unit

BE 573 Special Topics in Bioengineering - 1
This special topics course will focus on emerging topics in Bioengineering at the molecular and cellular level covering genomics, epigenetics, molecular and cellular systems with focus on immunology, cancer, neuroengineering, biomechanics, and other facets of bioengineering
Taught by: BE Staff
Course usually offered in spring term
Activity: Lecture
1.0 Course Unit

BE 574 Special Topics in Bioengineering -2
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
Taught by: BE Staff
Course usually offered in spring term
Activity: Lecture
1.0 Course Unit

BE 575 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.
Course usually offered in fall term
Prerequisites: Graduate Standing or permission of the instructor.
Activity: Lecture
1.0 Course Unit
Notes: Auditors not permitted

BE 576 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.
Course usually offered in fall term
Prerequisites: Graduate Standing or permission of the instructor.
Activity: Lecture
1.0 Course Unit
Notes: Auditors not permitted

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Course usually offered in fall term
Prerequisites: Graduate Standing or permission of the instructor.
Activity: Lecture
1.0 Course Unit
Notes: Auditors not permitted
BE 581 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.
Taught by: Song and Wehrli
Course offered spring; odd-numbered years
Also Offered As: BMB 581
Activity: Lecture
1.0 Course Unit

BE 583 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.
Course usually offered in fall term
Also Offered As: BE 483, MPH 602
Prerequisites: MATH 241, BIOL 215, BE 305
Activity: Lecture
1.0 Course Unit

BE 584 Mathematics of Medical Imaging and Measurements
In the last 25 years there has been a revolution in image reconstruction techniques in fields from astrophysics to electron microscopy and most notably in medical imaging. In each of these fields one would like to have a precise picture of a 2 or 3 dimensional object which cannot be obtained directly. The data which is accessible is typically some collection of averages. The problem of image reconstruction is to build an object out of the averaged data and then estimate how close the reconstruction is to the actual object. In this course we introduce the mathematical techniques used to model measurements and reconstruct images. As a simple representative case we study transmission X-ray tomography (CT). In this context we cover the basic principles of mathematical analysis, the Fourier transform, interpolation and approximation of functions, sampling theory, digital filtering and noise analysis.
Course not offered every year
Also Offered As: AMCS 584, MATH 584
Prerequisites: MATH 314, 360, 361 or 508 and 509
Activity: Lecture
1.0 Course Unit

BE 597 Master's Thesis Research
For students working on an advanced research program leading to the completion of master's thesis.
One-term course offered either term
Activity: Masters Thesis
1.0 Course Unit

BE 599 Master's Independent Study
The purpose of BE 599 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
One-term course offered either term
Activity: Independent Study
1.0 Course Unit

BE 608 Commercializing Translational Therapeutics
To provide an in-depth view of the process by which scientific discoveries are commercialized. This course covers discovery in the laboratory, technology transfer, regulatory, financial, and managerial issues involved in moving a technology from the lab into the market place. The course contents fall into three broad categories: (1) examples of scientific discoveries that are candidates for commercialization, (2) fundamental elements of technology transfer, such as intellectual property protection and licensing, and (3) aspects of commercialization, such as regulatory approval, financing, and startup formation. In using this structure, the course provides parallel coverage of both the science and the commercialization process, in such a way that the elements of one contribute to the student's experience in learning the other. Prerequisite: Undergraduates and graduate students in other departments are welcome. Please contact mmaxwell@upenn.edu to request permission to request permission to register.
Taught by: R. Mauck, R. Wells.
Course offered spring; even-numbered years
Also Offered As: MTR 703
Prerequisite: BIOM 600
Activity: Lecture
1.0 Course Unit

BE 640 The Extracellular Matrix
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.
Taught by: Nalaka Gooneratne, MD
Course offered spring; even-numbered years
Also Offered As: CAMB 703
Prerequisite: BIOM 600
Activity: Lecture
1.0 Course Unit

BE 650 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.
Course usually offered in fall term
Activity: Lecture
1.0 Course Unit

BE 662 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.
Course usually offered in fall term
Also Offered As: CBE 618, MEAM 662
Activity: Lecture
1.0 Course Unit
**BE 699 Bioengineering Seminar**
This is a required course for BE PhD candidates and involves attendance at seminars related to bioengineering topics, which can be either within the departmental seminar series or through other relevant seminar series on campus. The goal is to expose students to a breadth of bioengineering topics beyond their specific dissertation work. Students are required to submit summaries of the attended seminars to receive course credit. 
One-term course offered either term
Activity: Seminar
0.5 Course Units

**BE 711 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.
Taught by: Rebecca Wells
Course usually offered in fall term
Also Offered As: CAMB 711
Activity: Lecture
1.0 Course Unit

**BE 899 PhD Independent Study**
The purpose of BE 899 is to allow a student to create a customized curriculum to study material beyond or outside the scope of our standard BE course offerings. Rather than a research or design project, BE 899 is a one-on-one or small-group course with a professor. Students must submit a proposal outlining the study area along with the professor’s approval. A paper or presentation is required.
One-term course offered either term
Activity: Independent Study
1.0 Course Unit
Notes: Graduate Students Only

**BE 990 Masters Thesis**
For Master’s students who have completed the course requirements for the Master’s degree and are strictly working to complete the Master’s Thesis leading to the completion of a Master’s degree. Permission Required.
One-term course offered either term
Activity: Masters Thesis
1.0 Course Unit

**BE 995 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
One-term course offered either term
Prerequisites: For Ph.D. Candidates only
Activity: Dissertation
1.0 Course Unit

**BE 999 Thesis/Dissertation Research**
For students working on an advanced research program leading to the completion of master’s thesis or Ph.D. dissertation requirements.
One-term course offered either term
Activity: Independent Study
1.0 Course Unit