

# EN.580 (BIOMEDICAL ENGINEERING)

## Courses

### EN.580.110. Immersive Summer Program for Education, Enrichment, and Distinction in Biomedical Engineering. 3 Credits.

This cross-disciplinary, project-based course will introduce students to the field of biomedical engineering with particular emphasis on applying engineering principles to solve problems related to human health. Throughout the course, students will learn and implement modern techniques and methodology to address biomedical questions using biological, computational, and design approaches. Students will (1) apply molecular biology, cell culture, and other wet-lab techniques to answer hypothesis-driven experimental questions; (2) apply programming, coding, and machine learning techniques to analyze data and model disease; and (3) work in small groups to identify, design, and prototype solutions to unmet clinical needs. Guest lectures and workshops will round out the course, introducing students to careers in biomedical engineering, enhancing professional development skills, and providing other tools necessary for future success in the field.

### EN.580.111. Biomedical Engineering and Design. 2 Credits.

Working in teams with upperclassmen this course (1) introduces biomedical engineering freshmen to an orderly method for analyzing and modeling biological systems, (2) introduces engineering principles to solve design problems that are biological, physiological, and/or medical, and (3) considers the ethical and professional responsibility in developing biomedical engineering solutions to health care challenges. Freshmen are expected to use the informational content being taught in calculus, physics and chemistry and to apply this knowledge to the solution of practical problems encountered in biomedical engineering. BME Freshmen only.

**Prerequisite(s):** Students must have completed Lab Safety training prior to registering for this class.

Area: Engineering, Natural Sciences

### EN.580.112. Design Team Health-Tech Project II. 3 Credits.

A two-semester course sequence where freshmen work with groups of BME upperclassmen mentors, and learn to use engineering principles to solve design problems that are biological, physiological, and/or medical. Freshmen are expected to use the informational content being taught in calculus, physics, and chemistry and apply this knowledge to the solution of practical problems encountered in biomedical engineering.

Area: Engineering, Natural Sciences

### EN.580.151. Structural Biology of Cells. 3 Credits.

Course provides a rigorous foundation in cell structures and pathways relevant to medicine and bioengineering. Interactive lectures will cover molecular components (biological membranes, proteins, DNA, RNA, glycoproteins); electro-chemical gradients across membranes; structure and functions of the cell nucleus and genome; secretory and endocytic pathways; biomechanics, contractility and cell motility; cell adhesions, tissues and the extracellular matrix; signaling structures and networks; stem cells, cell division and cell specialization; heredity, mutations and phenotypes. This course will feature bioengineering principles including shape, localization, timing and feedback in biological systems. Students also take the 1-credit Structural Biology of Cells Lab.

Area: Engineering, Natural Sciences

### EN.580.153. Structural Biology of Cells Laboratory. 1 Credit.

Students will learn how to analyze biological data in computational labs that focus on protein 3D structural data (Structural Protein Engineering), DNA/genomics data (Genomes to Clinical Phenotypes) and live-cell imaging data (Molecular Tracking in Cells) to gain an integrated understanding of cells, tissues and the molecular basis of disease. This lab accompanies the 3-credit Structural Biology of Cells course to provide a rigorous foundation in cell structures, pathways and strategies relevant to medicine and bioengineering.

Area: Engineering, Natural Sciences

### EN.580.204. Social Justice: Fndts & Personal Commitments. 3 Credits.

The course will teach historical concepts from the post civil war years to #blacklivesmatter and will cover key periods in the American experience including Reconstruction, Jim Crow, the struggle for civil rights, and #blacklivesmatter. The course emphasizes an understanding of both policy and practice, and engages students in series of case studies, practical frameworks, selected readings, and guest lectures. Students will contemplate and study the ways in which racial justice plays out across a variety of contexts, including public spaces, the workplace, school, family and relationships, and public policy. This series of guest lectures will be delivered by practitioners and leaders in the movement for racial justice. Ultimately, the course aims to empower students to advance racial justice through self, individual and systems advocacy. At the end of the course, students can expect to walk away with a) a broad understanding of the drivers of structural racism, b) models of advocacy in advancing policy change, c) individual and institutional core competencies for anti-racist practices. Recommended background: an authentic interest in racial justice and models for social change, a willingness to engage in candid, constructive, and challenging conversations and a desire to learn tools with practical applications in the workforce, community organizing, and social activism.

Area: Social and Behavioral Sciences

### EN.580.211. Design Team Health-Tech Project I. 3 Credits.

Sophomore-level version of EN.580.311-312 or Perm. Req'd

Area: Engineering, Natural Sciences

### EN.580.212. Design Team Health-Tech Project II. 3 Credits.

Sophomore-level version of EN.580.111-112. Permission of course directors required.

Area: Engineering, Natural Sciences

### EN.580.221. Biochemistry and Molecular Engineering. 4 Credits.

This combined lecture and laboratory course will delve into the workings of the cell and the interactions between cells. The emphasis in this course is on quantitative analysis of reactions between molecules, including receptor-ligand and antigen-antibody specificity, enzyme catalysis, genetic information, protein processing and secretion, cell physiology and cell functions. In the laboratory portion of the course students will gain experimental skills in enzyme kinetics, binding (specificity and affinity), DNA analysis techniques (PCR, forensics), metabolism, membrane potentials and molecular neuroscience. The course will be supplemented with discussion and analysis of classic papers in the field as well as the current literature. Recommended background: Structural Biology of the Cell or a strong background in molecular biology and Chemistry.

Area: Natural Sciences

**EN.580.237. Neuro Data Design I. 3 Credits.**

In this year long course, students will work together in small teams to design, develop, and deploy a functioning tool for practicing brain scientists, either for accelerating research or augmenting the clinic. The first semester will focus on scoping the tool, including determining feasibility (for us in a year) and significance (for the targeted brain science community), as well as a statement of work specifying deliverables and milestones. The second semester will focus on developing the tool, getting regular feedback, and iterating, using the agile/lean development process. This version of Neuro Data Design is designed for students with less coding experience who wish to develop their writing skills.

Area: Engineering  
Writing Intensive

**EN.580.238. Neuro Data Design II. 3 Credits.**

In this year long course, students will work together in small teams to design, develop, and deploy a functioning tool for practicing brain scientists, either for accelerating research or augmenting the clinic. The first semester will focus on scoping the tool, including determining feasibility (for us in a year) and significance (for the targeted brain science community), as well as a statement of work specifying deliverables and milestones. The second semester will focus on developing the tool, getting regular feedback, and iterating, using the agile/lean development process. This version of Neuro Data Design is designed for students with less coding experience who wish to develop their writing skills.

Area: Engineering  
Writing Intensive

**EN.580.241. Statistical Physics. 2 Credits.**

Basic principles of statistical physics and thermodynamics of biological systems. Topics included quantitative statistical formulation of entropy and its application in thermodynamic optimization and conversion principles, the Gibbs/Boltzmann distribution, mixing, and phase transitions. Recommended Background: AS.110.108-109, AS.030.101-102, AS.171.101-102 or equivalent.

Area: Engineering

**EN.580.242. Biological Models and Simulations. 2 Credits.**

This course introduces students to modeling and analysis of linear biological systems. Topics include viscoelastic materials, pharmacokinetics, reaction-diffusion-convection equation with applications to molecular transport in tissues. The course also introduces students to the Matlab programming language, which allows them to implement the models discussed in the classroom. Recommended course background: AS.110.201 Linear Algebra, AS.110.302 Differential Equations, or EN.553.291 Linear Algebra and Differential Equations.

Area: Engineering

**EN.580.243. Linear Signals and Systems. 2 Credits.**

An introduction to signals and linear systems. Topics include first and second order systems, linear time variant discrete and continuous systems, convolution, Fourier series, and Fourier transforms. Recommended background: AS.171.102 and AS.110.201, AS.110.302, or 553.291. 110.302 may be taken at the same time.

Area: Engineering

**EN.580.244. Nonlinear Dynamics of Biological Systems. 2 Credits.**

Analysis and simulation of nonlinear behavior in biological systems: bifurcations (cell-fate decision), limit cycles (cell-cycle, neuronal excitations), chaos, and maps. Matlab will be used to simulate these systems and motivate nonlinear analytic tools and stability analysis. Recommended course background: AS.110.201 Linear Algebra, AS.110.302 Differential Equations, or EN.553.292 Linear Algebra and Differential Equations.

Area: Engineering

**EN.580.246. Systems and Controls. 2 Credits.**

An introduction to the analysis and synthesis of controllers for linear systems. Topics include Laplace transforms, input output and state space representations of linear systems, stability, observability, controllability, and PID controller design. Recommended course background: AS.110.201 Linear Algebra, AS.110.302 Differential Equations, or EN.553.291 Linear Algebra and Differential Equations.

**Prerequisite(s):** EN.580.243

Area: Engineering

**EN.580.248. Systems Biology of the Cell. 2 Credits.**

Cellular systems biology provides a theoretical and quantitative understanding of the interactions between DNA, RNA, and proteins that create the well-regulated system we call life. This course develops first-principles models for the central dogma of molecular biology: information flow through protein signal transduction pathways, gene regulation by protein-DNA physical interactions, transcription of DNA to RNA, translation of RNA to protein, and feedback regulation that closes the cycle. Topics include complex analysis and contour integrals, spectral transforms, linear models for cell signaling, positive and negative feedback, non-linearities introduced by saturation and cooperativity, information content and combinatorial regulation, and instabilities leading to cell fate specification. Recommended Course Background: Linear Algebra, Systems and Controls and programming.

Area: Engineering, Natural Sciences

**EN.580.298. Advanced Design Team. 3 Credits.**

Sophomore-level version of EN.580.498. This independent course will provide project-specific mentorship and guidance for a team to complete a sophisticated prototype and demonstrate technical feasibility towards impacting a clinical problem. Prototyping and testing tools and procedures will be taught and employed on a per-project basis. Documentation of progress through a design history file and course report is required. Teams will meet biweekly with course faculty through a Desk Review format. Students are expected to work in teams between desk reviews and present progress updates as well as short- and long-term action plans at each desk review. A final presentation is expected at the end of the semester that will involve course faculty as well as a clinical sponsor (called a committee meeting in Design Teams). Additionally, each team must identify a domain expert from the WSE faculty that agrees to attend the final presentation and at least 2 desk reviews. This faculty will focus on guiding and assessing the team's technical achievements within the context of biomedical instrumentation.

**Prerequisite(s):** Students must have completed Lab Safety training prior to registering for this class. To access the tutorial, login to myLearning and enter 458083 in the Search box to locate the appropriate module.

**EN.580.311. Design Team Health-Tech Project I. 3 Credits.**

A two-semester course sequence where juniors and seniors work with a team leader and a group of BME freshmen and sophomores, to solve open-ended problems in biomedical engineering. Upperclassmen are expected to apply their general knowledge and experience, and their knowledge in their concentration area, to teach lower classmen and to generate the solution to practical problems encountered in biomedical engineering. Perm. Req'd.

Area: Engineering, Natural Sciences

**EN.580.312. Design Team Health-Tech Project II. 3 Credits.**

A two semester course sequence where juniors and seniors work with a team leader and a group of BME freshmen and sophomores, to solve open-ended problems in biomedical engineering. Upperclassmen are expected to apply their general knowledge and experience, and their knowledge in their concentration area, to teach lower classmen and to generate the solution to practical problems encountered in biomedical engineering.

Area: Engineering, Natural Sciences

**EN.580.336. Distinguished Seminar Series in Computational Medicine. 1 Credit.**

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

**EN.580.404. Design Team Project Definition. 0.5 Credits.**

This course will train student BME Design Teams to identify and assess project options for their BME Design Team year-long project the subsequent year. Students will learn clinical observation tools, root cause analysis and need filtering. The outcome of the course is the ranking, justification and selection of the Design Team project.

**EN.580.408. Design Team Leader Project Management. 1 Credit.**

This course prepares undergraduate students to lead teams for the subsequent Design Teams course. This course will teach leadership skills, expose students to project options and clinical sponsors, and prepare them to plan and execute a biomedical design project. Course will meet in the Clark Hall Design Studio and the Carnegie Building (SoM) Design Studio.

**EN.580.410. Effective Teaching and Management of Engineering Teams. 2 Credits.**

Senior biomedical engineering students will assist the core course instructors and PhD students in managing the sections and recitations and or lab component of a course. Permission required.

**EN.580.411. Design Team Health-Tech Project I. 3 Credits.**

Perm. Req'd. Senior-level version of EN.580.311-312.

Area: Engineering

**EN.580.412. Design Team Health-Tech Project II. 3 Credits.**

Senior-level version of EN.580.311-312. Permission of course directors required

Area: Engineering

**EN.580.413. Design Team Leader I. 1 Credit.**

This course is for Design Team leaders actively leading a team for the academic year. This course focuses on development of leadership, communication and team management skills in the context of biodesign. Area: Engineering

**EN.580.414. Design Team Leader III. 1 Credit.**

This course is for Design Team leaders actively leading a team for the academic year. This course focuses on development of leadership, communication and team management skills in the context of biodesign. Area: Engineering

**EN.580.418. Principles of Pulmonary Physiology. 3 Credits.**

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

Area: Engineering, Natural Sciences

**EN.580.419. Philosophy of Life: A Data Science Perspective. 3 Credits.**

We all want to flourish. Whatever it means, however we each uniquely define it, our desire to flourish is the primary driving force in each of our lives. But what does that mean? And how do we do it? Lots of people—poets, mystics, theologians, philosophers—have attempted to describe what constitutes flourishing. But we don't really understand what they are talking about. We believe if we did understand their guidance, we could flourish more. Previous teachings, however, typically lacked access to recent developments in neural and cognitive sciences (natural intelligence) and also machine learning and computer science (artificial intelligence). We therefore describe what we think flourishing means, and how to achieve it, using modern insights from intelligence sciences. Our goal is to describe the path to increased flourishing using concepts that anyone can understand. Our belief is that a deeper understanding of these concepts will facilitate greater collective flourishing. Recommended background courses: Basic Probability and Statistics.

Area: Humanities

**EN.580.420. Immunomodulatory Biomaterials: Design, Synthesis, and Applications. 3 Credits.**

The objective of this course is to teach students the chemistry, immunology, and materials engineering fundamentals necessary to develop novel materials that modulate immune responses for the treatment and prevention of diseases. This course will present many of the small molecule and polymer chemistry strategies used to synthesize state-of-the-art biomaterials. The concepts of spatio-temporal delivery of therapeutics, biomaterials degradation, biocompatibility, and various structure-function relationships between biomaterials and the immune system will be introduced. The role played by adaptive and innate immunity in the development and persistence of cancer, infectious diseases, and autoimmunity will be explored. Emphasis will be placed on the design elements that have been, and could be, engineered into immunomodulatory materials to improve human health outcomes.

Recommended background: Organic Chemistry I

**Prerequisite(s):** Students must have completed Lab Safety training prior to registering for this class.

Area: Engineering, Natural Sciences

**EN.580.424. Neuroengineering and Lab. 3 Credits.**

A laboratory course in which various physiological preparations are used as examples of problems of applying technology in biological systems. The emphasis in this course is on the design of experimental measurements and on physical models of biological systems.

**Prerequisite(s):** Students must have completed Lab Safety training prior to registering for this class. To access the tutorial, login to myLearning and enter 458083 in the Search box to locate the appropriate module.

Area: Engineering, Natural Sciences

**EN.580.425. Radiology for Engineers. 3 Credits.**

This course provides engineering students with an introductory understanding of the principles and practice of radiology – including a spectrum of specialties in diagnostic radiology as well as procedures in interventional radiology and digital pathology. The course includes lectures, working with real image data, and visits to clinical areas at Johns Hopkins Hospital. Each segment of the course emphasizes clinical perspective on imaging (including scanner technology and image analysis) in relation to anatomy, physiology, and pathology. Each segment is led by an expert in a particular discipline in collaboration with the course director. Recommended course background: 580.472, 601.455. The course is open to senior BME undergraduates. Enrollment is limited by permission from the course director. Audits are not allowed.

Area: Engineering, Natural Sciences

**EN.580.426. Neuroengineering: The Neural Control of Movement. 3 Credits.**

This half-semester course will delve into how the brain encodes and controls movement. The emphasis in this course is on the theoretical, computational, and experimental approaches that provide the basis of our understanding of how we interact with the world. Lectures will focus on the neural circuits underlying sensorimotor transformations, population coding, motor learning and plasticity, decision-making, functional brain imaging, brain stimulation, and brain machine interfacing. Students will compare neural imaging techniques. The course will be supplemented with visits to medical campus labs and critical analysis of current literature.

Area: Engineering, Natural Sciences

**EN.580.427. Microphysiological Systems and Laboratory. 3 Credits.**

This course focuses on the principle and application of biological and engineering fundamentals to design microphysiological systems such as organ/tissue chips, 3D-printed tissues, and organoids. This course will introduce the concept of human organ-on-a-chip and organoid engineering and discuss the latest developments in the field of drug development - the shift from animal testing toward human relevant, high content, high-throughput integrative testing strategies. Students will learn various biofabrication techniques such as microfluidics, microfabrication, and 3D bioprinting to create in vitro miniaturized 3D complex human tissue models that mimic the biochemical, electrical, and mechanical properties of organ or tissue function. This course will also cover a wide range of biomedical applications of microphysiological systems in disease modeling, drug screening, precision medicine, and space biology as well as technology commercialization efforts. This laboratory portion of the course consists of three experiments that will provide students with valuable hands-on experience in design, fabrication and applications of microphysiological systems, including organ-on-a-chip systems (tissue/organ chips), 3-D printed tissue constructs, and organoids. Experiments include 1) the basics of human induced pluripotent stem cell differentiation, 2) tissue/organ chip fabrication, and 3) functional phenotypic analysis and drug testing. Spring semester only.

Recommended background: EN.580.441, EN.580.442 and EN.580.452

Area: Engineering

**EN.580.428. Genomic Data Visualization. 3 Credits.**

As the primary mode through which analysts and audience members alike consume data, data visualization remains an important hypothesis generating and analytical technique in data-driven research to facilitate new discoveries. However, if done poorly, data visualization can also mislead, bias, and slow down progress. This hands-on course will cover the principles of perception and cognition relevant for data visualization and apply these principles to genomic data, focusing on large-scale single-cell and spatially-resolved omics datasets, using the R statistical programming language. Students will be expected to complete class readings, create weekly data visualizations as homework assignments, and make a major class presentation."

Area: Engineering

**EN.580.430. Systems Pharmacology and Personalized Medicine. 4 Credits.**

We have moved beyond the 'one-size-fits-all' era of medicine. Individuals are different, their diseases are different, and their responses to drugs are different too. This variability is not just from person to person; heterogeneity is observed even between tumors within the same person, and between sites within the same tumor. These levels of variability among the human population must be accounted for to improve patient outcomes and the efficiency of clinical trials. Some of the ways in which this is being explored include: drugs are being developed hand-in-hand with the tests needed to determine whether or not they will be effective; tumor fragments excised from patients are being cultured in the lab for high-throughput testing of drugs and drug combinations; data-rich assays such as genomics and proteomics identify thousands of potentially significant differences between individuals; and computational models are being used to predict which therapies will work for which patients. This course will focus on the applications of pharmacokinetics and pharmacodynamics to simulating the effects of various drugs across a heterogeneous population of diseased individuals. Such computational approaches are needed to harness and leverage the vast amounts of data and provide insight into the key differences that determine drug responsiveness. These approaches can also explore the temporal dynamics of disease and treatment, and enable the modification of treatment during recovery. Most of the assignments in this course involve some coding and visualization of data (we use Matlab and R), and students undertake a project to simulate a drug or other treatment of their choice. Recommended background: 110.201 Linear Algebra, 110.302 Differential Equations, and 553.311 Probability and Statistics (or equivalent).

Area: Engineering

**EN.580.431. Introduction to Computational Medicine: Imaging. 2 Credits.**

Computational medicine is an emerging discipline in which computer models of disease are developed, constrained using data measured from individual patients, and then applied to deliver precision health care. This course will cover computational anatomy. Students will learn how to: model anatomies using magnetic resonance imaging data; compare anatomies via mappings onto anatomical atlases; discover anatomical biomarkers of disease; analyze changes in the connectivity of anatomies in disease. Class time will emphasize hands-on learning through data analysis, software development, and simulation. All instructional materials will be made available at the beginning of the course. Recommended Course Background: Matlab or Python. This course can be taken in conjunction with EN.580.433 which covers computational physiological medicine.

**Prerequisite(s):** ( AS.110.107 OR AS.110.109 OR AS.110.113) AND ( EN.553.310 OR EN.553.311 OR EN.553.420 OR EN.553.421 OR EN.553.430 OR EN.560.348 )

**EN.580.432. Principles of Genomic Systems Engineering and Synthetic Biology. 3 Credits.**

Biomedical engineering has always involved interfacing with biological systems using non- or partially-biological devices. A current frontier is the ability to interface with biological systems from within using genetic systems. This course focuses on principles of engineering genetic systems. Students will learn how to design a genetic effector circuit, insert it cells and tissues, and assess its function. Specific concepts that will be covered include cellular engineering, gene editing, CRISPR, cloning, gene delivery, viral engineering, barcoding, genetic recording, spatial sequencing, and in situ sequencing.

**Prerequisite(s):** EN.580.452 OR EN.580.454

Area: Engineering, Natural Sciences

**EN.580.433. Introduction to Computational Medicine: The Physiome. 2 Credits.**

Computational medicine is an emerging discipline in which computer models of disease are developed, constrained using data measured from individual patients, and then applied to deliver precision health care. Computational physiological medicine: develops computational models of disease at the cellular, tissue, organ, and organism level; develops methods for constraining these models using patient data; applies these models to better treat patients. Students will learn how to: use biophysical laws and data to formulate computational models of physiological systems in health and disease; analyze the behaviors of these models using analytical and simulation approaches; apply models to understand their use in diagnosing and treating disease. Class time will emphasize hands-on learning through data analysis, software development, and simulation. All instructional materials will be made available at the beginning of the course. Recommended Course Background: C++, Matlab or Python.

**Prerequisite(s):** (AS.110.107 OR AS.110.109 OR AS.110.113) AND (EN.553.310 OR EN.553.311 OR EN.553.420 OR EN.553.430 OR EN.560.348)

Area: Engineering, Natural Sciences

**EN.580.435. Applied Bioelectrical Engineering. 3 Credits.**

This course covers diverse applications of bioelectrical measurements, manipulation and therapy in engineering practice. Topics include functional electrical stimulation, deep brain stimulation, cardiac pacing and defibrillation, tissue ablation and electromanipulation of cells. Students will receive practical training in the simulation of electrical potentials and electric fields in volume conductors, using the finite element package COMSOL. It will be used throughout the course to explore theoretical concepts as well as in a class project. Recommended background: familiarity with MATLAB; cardiac, muscle and brain physiology; and cellular electrophysiology.

Area: Engineering

**EN.580.437. Biomedical Data Design. 4 Credits.**

In this year long course, students will work together in small teams to design, develop, and deploy a functioning tool for practicing biomedical scientists, either for accelerating research or augmenting the clinic. The first semester will focus on scoping the tool, including determining feasibility (for us in a year) and significance (for the targeted brain science community), as well as a statement of work specifying deliverables and milestones. The second semester will focus on developing the tool, getting regular feedback, and iterating, using the agile/lean development process. Recommended Course Background: linear algebra, probability and statistics, numerical programming.

Area: Engineering, Natural Sciences

**EN.580.438. Biomedical Data Design II. 4 Credits.**

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

Area: Engineering

**EN.580.439. Models of the Neuron. 4 Credits.**

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

Area: Engineering, Natural Sciences

**EN.580.441. Cellular Engineering. 3 Credits.**

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

Area: Engineering, Natural Sciences

**EN.580.442. Tissue Engineering. 3 Credits.**

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

Area: Engineering, Natural Sciences

**EN.580.443. Advanced Orthopaedic Tissue Engineering. 3 Credits.**

This course is intended to provide a comprehensive overview on the current state of the field of Orthopaedic Tissue Engineering. Students will apply engineering fundamentals learned in the Tissue Engineering course (EN.580.442/642) with special emphasis on how they apply to bone, cartilage, and skeletal muscle tissue engineering. The development, structure, mechanics, and function of each of these tissues will be discussed. Key articles from the last three decades that focus on stem cell- and cell-free, biomaterial-based approaches to regenerate functional tissues will be presented and analyzed. Practical (regulatory/commercial) considerations that restrict the translation of therapies to the clinic will be discussed.

**Prerequisite(s):** Grade of B or higher in EN.580.442 OR EN.580.642  
Area: Engineering

**EN.580.444. Biomedical Applications of Glycoengineering. 3 Credits.**

This course provides an overview of carbohydrate-based technologies in biotechnology and medicine. The course will begin by briefly covering basics of glycobiology and glycochemistry followed by detailed illustrative examples of biomedical applications of glycoengineering. A sample of these applications include the role of sugars in preventative medicine (e.g., for vaccine development and probiotics), tissue engineering (e.g., exploiting natural and engineered polysaccharides for creating tissue or organs de novo in the laboratory), regenerative medicine (e.g., for the treatment of arthritis or degenerative muscle disease), and therapy (e.g., cancer treatment). A major part of the course grade will be based on class participation with each student expected to provide a "journal club" presentation of a relevant paper as well as participate in a team-based project designed to address a current unmet clinical need that could be fulfilled through a glycoengineering approach. Recommended Course Background: EN.580.221 Molecules and Cells. Area: Engineering, Natural Sciences

**EN.580.447. Computational Stem Cell Biology. 3 Credits.**

This course will provide the student with a mechanistic and systems biology-based understanding of the two defining features of stem cells: multipotency and self-renewal. We will explore these concepts across several contexts and perspectives, emphasizing seminal and new studies in development and stem cell biology, and the critical role that computational approaches have played. The course will start with an introduction to stem cells and a tutorial covering computational basics. The biological contexts that we will cover thereafter include "Cell Identity", "Pluripotency and multipotency", "Stem cells and their niche", "Modeling cell fate decisions", and "Engineering cell fate". This class is heavily weighted by individual computational assignments. The motivation for this strategy is that regularly occurring, moderately-sized computational projects are the most efficient way to impart an understanding of our models of this extraordinary class of cells, and to inspire a sense of excitement and empowerment. Preferred background: familiarity with the UNIX shell. Recommended Background: EN.580.221 - Molecules and Cells or Equivalent.

**Prerequisite(s):** Students may take EN.580.447 or EN.580.647, but not both.

Area: Engineering, Natural Sciences

**EN.580.452. Cell and Tissue Engineering Lab. 3 Credits.**

This half-semester flipped-content laboratory course will consist of modules that provide students with valuable hands-on experience in cell and tissue engineering. Modules contain experiments including the basics of cell culture techniques, gene transfection, metabolic glycoengineering, and cell encapsulation. Students will collect and analyze their own experimental data, write-up results in publication structured reports, and engage in active discussion of current scientific literature. Students interested in or actively pursuing a Master's degree should prioritize the full semester 580.754 Cell & Tissue Engineering Lab. Textbook Info None. Pre-requisites Students must have completed the online "Introductory Laboratory Safety" and "Bloodborne Pathogens" prior to registering for this class. To access these courses, log in to MyLearning and identify these tutorials.

**Prerequisite(s):** Students must have completed Lab Safety training prior to registering for this class. To access the tutorial, login to myLearning and enter 458083 in the Search box to locate the appropriate module. Area: Engineering, Natural Sciences

**EN.580.453. Immunoengineering Principles and Applications with Laboratory. 3 Credits.**

This course focuses on the application of engineering fundamentals to design cell/tissue-based systems for modulating immune response in treating disease. Concepts of immune cell development, surveillance, migration, and activation/inhibition will be introduced. Students will learn tissues in the body important for trafficking of immune players to local sites of therapeutic response, as well as techniques used for their characterization. Engineering concepts required to alter immune cell or tissue function will be explored. Emphasis will be placed on synthetic biology methods such as viral or CRISPR-based techniques as well as necessary (pre/post) isolation and adoptive transfer techniques.

**Prerequisite(s):** Students must have completed Lab Safety training prior to registering for this class. To access the tutorial, login to myLearning and enter 458083 in the Search box to locate the appropriate module. Area: Engineering, Natural Sciences

**EN.580.454. Methods in Nucleic Acid Sequencing Lab. 3 Credits.**

Sequencing technology is a rapidly progressing field that requires experience in both wet (molecular biology) and dry (computational analysis) techniques. This laboratory course will consist of three experimental modules that will provide students with valuable hands-on experience in DNA sequencing and analysis. Students will learn basic sequencing library preparation, perform sequencing experiments and analyze the resulting data. Experiments include human targeted sequencing, metagenomic sequencing and genome assembly.

**Prerequisite(s):** Students must have completed Lab Safety training prior to registering for this class. To access the tutorial, login to myLearning and enter 458083 in the Search box to locate the appropriate module. Area: Engineering, Natural Sciences

**EN.580.456. Introduction to Rehabilitation Engineering. 3 Credits.**

The primary objective of this course is to introduce biomedical engineering students to the challenges of engineering solutions for persons functioning with disabilities and apply that knowledge to the development of a new, improved device to be used for measurement or treatment of an impairment or disability. In order to achieve this goal, the objectives of the fall semester include: gaining a basic appreciation of the modalities used to treat impairments, the opportunities for application of engineering to improve treatment delivery, understanding the science and engineering applied to helping persons with disabilities function in the everyday world and an basic knowledge of the legal, ethical issues and employment opportunities in rehabilitation engineering. By the conclusion of this class, students should be able to:

- Understand the breadth and scope of physical impairment and disability, including its associated pathophysiology
- Characterize the material and design properties of current evaluation tools for assessment of impairments and adaptations for disability
- Characterize the material and design properties of current modalities of treatment of impairments and adaptations for disability
- Apply engineering analysis and design principles to critique current solutions for persons with disabilities in order to suggest improvements

In the spring semester (in course EN.580.457), students will learn the biomedical engineering design process and its application to persons with disabilities. Working in groups of four to five, teams will work on a project derived from a needs analysis based on their visits to rehabilitation centers in the fall semester. Project will require instructor approval before the beginning of the spring semester. Each project will consist of a proposal for design of a new device or solution to a problem faced by persons with disabilities, preliminary "virtual" (e.g., CAD), and actual proof of concept working prototype.

**Prerequisite(s):** EN.580.424

Area: Engineering

**EN.580.457. Introduction to Rehabilitation Engineering: Design Lab. 3 Credits.**

Students have the opportunity to apply the knowledge they have gained in the fall semester of EN.580.456 and their prior coursework to the development of a new, improved device to be used for measurement or treatment of an impairment or disability. In doing so, they will learn the biomedical engineering design process and its application to persons with disabilities. Working in groups of four to five, teams will work on a project derived from a needs analysis based on their visits to rehabilitation centers in the fall semester. Project will require instructor approval before the beginning of the spring semester. Each project will consist of a proposal for design of a new device or solution to a problem faced by persons with disabilities, preliminary "virtual" (e.g., CAD), and actual proof of concept working prototype.

**Prerequisite(s):** Students must have completed Lab Safety training prior to registering for this class. To access the tutorial, login to myLearning and enter 458083 in the Search box to locate the appropriate module.;EN.580.456

Area: Engineering

**EN.580.458. Computing the Transcriptome. 3 Credits.**

This course will introduce computational tools used in the field of transcriptomics to analyze the genes and transcripts expressed in a living cell. Lectures will cover different practical ways to analyze large data sets generated by high-throughput RNA sequencing (RNA-Seq) experiments, including alignment, assembly, and quantification. The students will learn how to use RNA-seq to answer questions such as: what is the complete set of human genes? How do we reconstruct the splice variants that are transcribed in different cell types and conditions? How do we compute which genes are differentially expressed between different RNA-seq datasets? **Prerequisites:** (1) Familiarity with Python or Perl, (2) the Unix command-line environment, and (3) a basic understanding of programming in R.

Area: Engineering

**EN.580.459. Seminar in Epigenetic Engineering. 1 Credit.**

This is an interactive discussion course on topics in epigenetic engineering introduced by the instructor and the students, on cutting edge molecular and computational methods and applications to developmental biology and human disease research. It will be focused mostly on analysis of current literature as well as ongoing research in the Center for Epigenetics. **Background:** laboratory course in organic chemistry, biochemistry, or cell biology; introductory statistics; familiarity with R, Python, or Matlab

**Prerequisite(s):** Students must have completed Lab Safety training prior to registering for this class. To access the tutorial, login to myLearning and enter 458083 in the Search box to locate the appropriate module.

Area: Engineering, Natural Sciences

**EN.580.460. Epigenetics at the Crossroads of Genes and the Environment. 1.5 Credits.**

This is a seminar-style course focused on cutting edge molecular, cellular, mathematical, and computational biology of mammalian epigenetics and epigenomics in relationship to environmental exposure and human disease. The format is a Socratic-style seminar with three alternating components: (1) "Big Ideas" focused on general principles and especially questions from the students; (2) "Current Literature" focused on how to extract believable information in a reasonable time from current journal articles; and (3) "Methods Development" focused on how methods are invented, including computational genomics and engineering methods, with data analysis by the students. **Recommended background:** Laboratory course in organic chemistry, biochemistry, or cell biology; introductory statistics; familiarity with R, Python, or Matlab

Area: Engineering, Natural Sciences

**EN.580.462. Representations of Choice. 3 Credits.**

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

Area: Engineering

**EN.580.464. Advanced Data Science for Biomedical Engineering. 4 Credits.**

This course covers the basics of data science in biomedical engineering. The main topics include, introductory R, data cleaning, reproducible research, basic statistical inference, machine learning and artificial intelligence. Specific topics include: assessing diagnostic accuracy, basic probability, tidy data principles, prediction and data oriented web-app development using R/shiny. Students taking the course will learn a complete and practical pipeline of going from raw data to a data product. Suggest course background: proficiency in basic programming in at least one language, basic calculus, and linear algebra.

**EN.580.468. Practical Human Neuroimaging. 3 Credits.**

Neuroimaging is widely used in basic research and clinical practice. This course will introduce the basic principles of magnetic resonance imaging (MRI) and provide students with hands-on experience manipulating, analyzing, and interpreting MRI data sets. We will focus on four types of MRI used to understand human neuroscience: structural imaging, functional imaging, diffusion imaging, and perfusion imaging. After taking this course students will have a practical understanding of working with a variety of MRI data sets. Recommended background: Linear Algebra and programming experience (Python, Matlab, or C).

Area: Engineering

**EN.580.471. Principles of Design of BME Instrumentation. 4 Credits.**

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

Recommended Course Background: EN.520.345

**Prerequisite(s):** Students must have completed Lab Safety training prior to registering for this class. To access the tutorial, login to myLearning and enter 458083 in the Search box to locate the appropriate module.

Area: Engineering, Natural Sciences

**EN.580.475. Biomedical Data Science. 2 Credits.**

This course provides an introduction to data science and machine learning for biomedical engineering. The lectures cover topics in biomedical data processing (convolution, denoising, filtering, edge detection, template matching), biomedical data reduction (feature extraction, principal component analysis), and biomedical data regression, classification (including deep learning), and clustering. Background: Signals and Systems

**Prerequisite(s):** (AS.110.202 OR AS.110.211) AND (AS.110.201 OR AS.110.212 OR EN.553.291) AND (EN.553.310 OR EN.553.311 OR EN.560.348 OR EN.553.420 OR EN.553.421)

Area: Engineering, Natural Sciences

**EN.580.477. Biomedical Data Science Laboratory. 1 Credit.**

This course provides an introduction to data science and machine learning for biomedical engineering. The lectures cover topics in biomedical data processing (convolution, denoising, filtering, edge detection, template matching), biomedical data reduction (feature extraction, principal component analysis), and biomedical data regression, classification (including deep learning), and clustering. Recommended Course Background: Signals and Systems, Calculus III, Linear Algebra, Probability and Statistics.

Area: Engineering, Natural Sciences

**EN.580.479. Principles and Applications of Modern X-ray Imaging and Computed Tomography. 3 Credits.**

This course provides students with an intermediate-level understanding of the physics, engineering, algorithms, and applications (clinical, pre-clinical, and industrial) of x-ray imaging and computed tomography (CT). It is intended for senior undergraduates (EN.580.479) and/or graduate students (EN.580.679) in Biomedical Engineering, Computer Science, Electrical and Computer Engineering, or related fields in science and engineering. Topics include the physics of x-ray interaction and detection, image quality assessment, 3D image reconstruction (including analytical, iterative, and deep-learning approaches), and quantitative image data analysis. Guest lectures from clinical experts introduce applications in diagnostic and image-guided procedures. The students conduct experimental and computational projects involving acquisition and processing of x-ray CT data. Recommended background: Signals and Systems or an equivalent course and familiarity with Matlab.

Area: Engineering

**EN.580.480. Precision Care Medicine I. 4 Credits.**

Precision Care Medicine is a two-semester project-based learning course. Projects will use methods of machine learning and mechanistic and statistical modeling to develop novel data-driven solutions to important health care problems that arise in various areas of medicine including critical care medicine. The scope of such problems is vast and solutions can improve the delivery of patient care. Examples include data- and modeling-driven approaches to: optimal selection of patients to be admitted to ICUs; optimal determination of when it is safe to discharge a patient from an ICU; early prediction of pending changes in the clinical state of patients in an ICU; data-driven optimal selection of patient therapy; and others. In the first semester, students will assemble into teams of 5-6, and will work with their project mentors (clinical faculty in Johns Hopkins Medicine; Drs. Greenstein and Taylor) to develop a project work plan. In the remainder of the course, students will apply engineering approaches to solve the important health care problems in their projects. Class time will include: lectures and tutorials covering the physiology, medicine, and engineering principles relevant to each project; project work in a setting where faculty are available to assist students with challenges. HIPAA regulations and use of human subjects data will be covered. Each team will present project updates to the entire class at regular intervals so that every student becomes familiar with each project. Teams will be charged with designing, validating and deploying their model and an application that delivers the computational method for solving the underlying healthcare problem to the user. The goal is to generate results and one or more manuscripts to be submitted for publication by the end of the second semester.

Area: Engineering

Writing Intensive

**EN.580.481. Precision Care Medicine II. 4 Credits.**

Precision Care Medicine is a two-semester project-based learning course. Projects will use methods of machine learning and mechanistic and statistical modeling to develop novel data-driven solutions to important health care problems that arise in anesthesiology and critical care medicine. The scope of such problems is vast, and few have been approached before. Examples include data- and modeling-driven approaches to: optimal selection of patients to be admitted to ICUs; optimal determination of when it is safe to discharge a patient from an ICU; early prediction of pending changes in the clinical state of patients in an ICU; data-driven optimal selection of patient therapy; and others. In the first semester, students will assemble into teams of 3-4, and will work with their project mentors (clinical faculty in the ACCM Department; Drs. Winslow and Sarma) to develop a project work plan. In the remainder of the course, they will apply engineering approaches to solve the important health care problems in their projects. Class time will include: lectures and tutorials covering the physiology, medicine, and engineering principles relevant to each project; project work in a setting where faculty are available to assist students with challenges. Each team will present project updates to the entire class at regular intervals so that every student becomes familiar with each project. Teams will also be charged with designing, validating and deploying a web-application that delivers the computational method for solving the underlying healthcare problem to the user. HIPAA regulations, use of human subjects data, and requirements for FDA Class II and Medical Device Data Systems approval will be covered.

**Prerequisite(s):** (EN.580.480 OR EN.580.680)

Area: Engineering  
Writing Intensive

**EN.580.482. Precision Care Medicine III. 3 Credits.**

Precision Care Medicine III follows Precision Care Medicine I - II. Registration is open only to those students who have completed these courses and who wish to continue project course work under the mentorship of the Biomedical and Engineering PIs. Students will have regular meetings with their PIs.

**EN.580.483. Annotate a Genome. 3 Credits.**

The course will present practical and specific understanding of approaches for genome interpretation. Topics will include Common Variants, Rare and Novel Variants, Personal Genomics and the Environment, Ethical considerations in personal genomics, Structural Variation, Pharmacogenetic variants, and Genetic Trait Associations. Students will learn bioinformatic methods to predict the impact of variants and to rapidly pull published information about variants identified in a genome. Students will work in teams to do exercises and programming projects on personal genomics datasets. Recommended Background: prior coursework in Genetics, Intermediate Programming  
Area: Quantitative and Mathematical Sciences

**EN.580.485. Computational Medicine: Cardiology. 2 Credits.**

A quantitative, model-oriented investigation of the cardiovascular system. The course will focus on cardiac electrophysiology, mechanics, and hemodynamics using multi-scale physiology-driven models.  
Area: Engineering, Natural Sciences

**EN.580.487. Computational Medicine: Cardiology Laboratory. 1 Credit.**

A laboratory course in which various physiological preparations are used as examples of problems of applying technology in biological systems. The emphasis in this course is on the design of experimental measurements and on physical models of biological systems.

**Prerequisite(s):** Students must have completed Lab Safety training prior to registering for this class. To access the tutorial, login to myLearning and enter 458083 in the Search box to locate the appropriate module.  
Area: Engineering, Natural Sciences

**EN.580.488. Foundations of Computational Biology and Bioinformatics. 3 Credits.**

This course is designed to give students a foundation in the basics of statistical and algorithmic approaches developed in computational biology/bioinformatics over the past 30 years, while emphasizing the need to extend these approaches to emerging problems in the field. Topics covered include probabilistic modeling applied to biological sequence analysis, supervised machine learning, interpretation of genetic variants, cancer genomics bioinformatic workflows and computational immuno-oncology. Attending the lab section "Annotate Your Genome" is required.

**Prerequisite(s):** EN.601.220

Area: Engineering, Natural Sciences

**EN.580.491. Learning, Estimation and Control. 3 Credits.**

The course introduces the probabilistic foundations of learning theory. We will discuss topics in regression, estimation, optimal control, system identification, Bayesian learning, and classification. Our aim is to first derive some of the important mathematical results in learning theory, and then apply the framework to problems in biology, particularly animal learning and control of action. Recommended Course Background: AS.110.201 and AS.110.302

Area: Engineering

**EN.580.493. Imaging Instrumentation. 4 Credits.**

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

**Prerequisite(s):** Students must have completed Lab Safety training prior to registering for this class. To access the tutorial, login to myLearning and enter 458083 in the Search box to locate the appropriate module.  
Area: Engineering

**EN.580.494. Build an Imager. 3 Credits.**

In this hands-on course, students will build an imaging device and learn to apply signals and systems knowledge in imaging system characterization, optimization, and post-processing. The course includes an introduction to two-dimensional signal processing techniques, basic imaging principles, imaging systems modeling, and optimization methods.

**Prerequisite(s):** Students must have completed Lab Safety training prior to registering for this class, or permission of the instructor.

Area: Engineering

**EN.580.497. Advanced Design Projects. 3 Credits.**

This course will provide project-specific mentorship and guidance for a team to complete a sophisticated prototype and demonstrate technical feasibility towards impacting a clinical problem. Prototyping and testing tools and procedures will be taught and employed on a per-project basis. Documentation of progress through a design history file and course report is required. Teams will meet biweekly with course faculty through a Desk Review format. Students are expected to work in teams between desk reviews and present progress updates as well as short- and long-term action plans at each desk review. A final presentation is expected at the end of the semester that will involve course faculty as well as a clinical sponsor (called a committee meeting in Design Teams). Additionally, each team must identify a domain expert from the WSE faculty that agrees to attend the final presentation and at least 2 desk reviews. This faculty will focus on guiding and assessing the team's technical achievements within the context of biomedical instrumentation.

**Prerequisite(s):** Students must have completed Lab Safety training prior to registering for this class. To access the tutorial, login to myLearning and enter 458083 in the Search box to locate the appropriate module.

Area: Engineering

**EN.580.498. Advanced Design Projects: Genomics and Systems Biology. 3 Credits.**

This course will provide project-specific mentorship and guidance for a team to complete a sophisticated prototype and demonstrate technical feasibility towards impacting a clinical problem. Prototyping and testing tools and procedures will be taught and employed on a per-project basis. Documentation of progress through a design history file and course report is required. Teams will meet biweekly with course faculty through a Desk Review format. Students are expected to work in teams between desk reviews and present progress updates as well as short- and long-term action plans at each desk review. A final presentation is expected at the end of the semester that will involve course faculty as well as a clinical sponsor (called a committee meeting in Design Teams). Additionally, each team must identify a domain expert from the WSE faculty that agrees to attend the final presentation and at least 2 desk reviews. This faculty will focus on guiding and assessing the team's technical achievements within the context of biomedical instrumentation.

**Prerequisite(s):** Students must have completed Lab Safety training prior to registering for this class.

Area: Engineering

**EN.580.510. Biomedical Engineering Undergraduate Research. 1 - 3 Credits.**

Student participation in ongoing research activities. Research is conducted under the supervision of a faculty member and often in conjunction with other members of the research group.

**Prerequisite(s):** You must request Independent Academic Work using the Independent Academic Work form found in Student Self-Service: Registration, Online Forms.

**EN.580.550. Biomedical Engineering Group Undergraduate Research. 1 - 3 Credits.**

Student participation in ongoing research activities. Research is conducted under the supervision of a faculty member and often in conjunction with other members of the research group. This section has a weekly research group meeting that students are expected to attend.

**Prerequisite(s):** You must request Independent Academic Work using the Independent Academic Work form found in Student Self-Service: Registration, Online Forms.

**EN.580.561. Advanced Focus Area Research. 3 Credits.**

This course provides students with the opportunity to consider unsolved issues within their focus area, delve into the current cutting-edge research, and provide a synopsis of the next steps required to advance a particular field. "Advanced Focus Area Research" is a one-semester course in which students complete a research project, present their work, and write a publication ready manuscript under the guidance of their Primary Investigator (PI) and a Focus Area mentor. Priority to Junior and Senior BME majors. Recommended Course Background: Previous research experience. Students must complete the online Undergraduate Lab safety courses available through "MyLearning" including Bloodborne Pathogens, HIPAA, and any other online training as needed.

**Prerequisite(s):** Students must have completed Lab Safety training prior to registering for this class. To access the tutorial, login to myLearning and enter 458083 in the Search box to locate the appropriate module.; You must request Independent Academic Work using the Independent Academic Work form found in Student Self-Service: Registration, Online Forms.

Area: Engineering, Quantitative and Mathematical Sciences

**EN.580.571. Honors Instrumentation. 2 Credits.**

Student must have taken 580.471/771. Students will develop a term paper and patent application and carry out a hands-on individual or team project throughout the semester. Previous projects include design of EEG amplifier, voltage clamp and patch clamp, vision aid of blind, pacemaker/defibrillator, sleep detection and alert device, glucose sensor and regulation, temperature controller, eye movement detection and device control, ultrasound ranging and tissue properties, impedance plethysmography, lie detector, blood alcohol detector, pulse oximeter, etc.

**Prerequisite(s):** You must request Independent Academic Work using the Independent Academic Work form found in Student Self-Service: Registration, Online Forms.

**EN.580.583. Research For 3+1 Students. 3 Credits.**

Research for 3+1 students only. Lab confirmation and registration approval required. Course is graded P/F only.

**EN.580.601. Special Topics in Bioengineering Innovation and Design. 1 Credit.**

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

**EN.580.602. Special Topics in Bioengineering Innovation and Design. 1 Credit.**

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

**EN.580.603. Special Topics in Bioengineering Innovation & Design. 1 Credit.**

This year long seminar series features experts from the medical device industry, venture capital firms, FDA, patent attorneys, entrepreneurs, and many more. They will share their real-world insights into the medical device innovation and commercialization process. Some of the topics covered will include bioethics, regulatory and reimbursement planning, medical device recalls, good design practices, and entrepreneurial success stories. The overarching philosophy of this seminar series is to complement the theoretical and practical aspects of the program curriculum, by learning from the experiences and insights of professionals in the field. For CBID MSE students only.

**EN.580.607. Regulation of Medical Devices. 1 Credit.**

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

**EN.580.608. Identification and Validation of Medical Device Needs. 6 Credits.**

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

**EN.580.610. Intro to Business for Healthcare Innovation & Design. 3 Credits.**

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

**EN.580.611. Medical Device Design and Innovation. 4 Credits.**

This course introduces you to the process of medical device design and innovation. You will learn the art and skill of identifying medical device opportunities through observations, interviews, and research. Through a combination of lectures, hands on activities, and interactions with clinical stakeholders, you will gain the ability to identify unmet, unarticulated, and underserved needs. Subsequently, you will learn the process of developing well thought out conceptual designs that meet those needs. You will learn to apply an iterative approach towards innovation, by involving and engaging multiple stakeholders and their perspectives throughout the process. Throughout the course modules, you will also follow the journey of several innovative startups/products/ services, that started at JHU-CBID and went through the process outlined in this course.

**EN.580.612. Medical Device Design and Innovation. 4 Credits.**

For CBID MSE students only.

**EN.580.614. Evidence Generation for the Medical Device Innovator. 2 Credits.**

This course introduces engineering students to a holistic framework to create and implement an evidence generation strategy for translating their invention/ innovation to the marketplace- including regulatory, reimbursement, and overall clinical trial strategy. Students will apply the topics towards their ongoing master's team project to develop and present their overall evidence generation plan for market access.

**EN.580.618. Identification and Validation of Global Health Needs. 4 Credits.**

Limited to CBID students only

**EN.580.619. Bioengineering Innovation and Design - Global Health. 4 Credits.**

For CBID MSE students only. Registration with instructor's permission only.

**EN.580.620. Principles and Practice of Global Health Innovation and Design. 4 Credits.**

For CBID MSE students only. Instructor's Permission Required.

**EN.580.625. Structure and Function of the Auditory and Vestibular Systems. 3 Credits.**

This course will cover basic functions of the auditory and vestibular pathways responsible for perception of sound and balance. Topics include: hair cell structure and mechanotransduction, hair cell electromotility and cochlear active force production, hair cell synaptic signaling, cochlear development and role of glia in the inner ear, primary auditory and vestibular stimulus encoding, afferents and the first-order brainstem nuclei, as well as clinical consequences of peripheral damage, physiology of hearing loss, vestibular loss, tinnitus, hair cell regeneration and gene therapy. Moving more centrally, synaptic transmission and signal processing in central neurons, and complex sound perception and movement control will be discussed. Aspects such as speech perception, sound localization, vestibular reflexes, vestibular compensation, and self-motion perception are discussed with an integrated perspective covering perceptual, physiological, and mechanistic data. Grades will be based on participation in class, homework, and first-half and second-half exams (both in class, closed book, short answer/essay types). This course will meet on the School of Medicine campus. Recommended Background: general introduction to Neuroscience. Undergraduates with knowledge in Neuroscience welcome.

**EN.580.627. Deep Learning for Medical Imaging. 3 Credits.**

Recent advances in machine learning and deep convolutional neural networks in particular, coupled with computational capabilities offered by modern GPUs and increased data availability, have enabled application of deep learning (DL) techniques in medical imaging. Such applications extend beyond image analysis, with increased presence of DL in early stages of the image formation process, including image preprocessing, tomographic image reconstruction, and image postprocessing informed by the requirements of specific clinical tasks. This course will introduce the foundations of deep learning methods used in medical imaging for both image formation and analysis through hands-on assignments and projects in image denoising, tomographic reconstruction, artifacts correction, image segmentation, feature detection/classification, and single/multi-modality registration. Recommended course background: Python and Linear Algebra

**EN.580.628. Topics in Systems Neuroscience. 1 Credit.**

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

**EN.580.631. Introduction to Computational Medicine: Imaging. 2 Credits.**

Computational medicine is an emerging discipline in which computer models of disease are developed, constrained using data measured from individual patients, and then applied to deliver precision health care. This course will cover computational anatomy. Students will learn how to: model anatomies using magnetic resonance imaging data; compare anatomies via mappings onto anatomical atlases; discover anatomical biomarkers of disease; analyze changes in the connectivity of anatomies in disease. Class time will emphasize hands-on learning through data analysis, software development, and simulation. All instructional materials will be made available at the beginning of the course. In addition to lectures, students will also participate in section meetings. Section meetings will be offered at designated times/locations throughout the course term and will culminate with final course-wide project presentations. Recommended Course Background: Matlab or Python. This course can be taken in conjunction with EN.580.433 which covers computational physiological medicine.

**EN.580.632. Principles of Genomic Systems Engineering and Synthetic Biology. 3 Credits.**

Biomedical engineering has always involved interfacing with biological systems using non- or partially-biological devices. A current frontier is the ability to interface with biological systems from within using genetic systems. This course focuses on principles of engineering genetic systems. Students will learn how to design a genetic effector circuit, insert it cells and tissues, and assess its function. Specific concepts that will be covered include cellular engineering, gene editing, CRISPR, cloning, gene delivery, viral engineering, barcoding, genetic recording, spatial sequencing, and in situ sequencing. Recommended background: Cellular and Molecular Biology, Methods in Nucleic Acid Sequencing  
Area: Engineering, Natural Sciences

**EN.580.635. Applied Bioelectrical Engineering. 3 Credits.**

This course covers diverse applications of bioelectrical measurements, manipulation and therapy in engineering practice. Topics include functional electrical stimulation, deep brain stimulation, cardiac pacing and defibrillation, tissue ablation and electromanipulation of cells. Students will receive practical training in the simulation of electrical potentials and electric fields in volume conductors, using the finite element package COMSOL. It will be used throughout the course to explore theoretical concepts as well as in a class project. Recommended background: familiarity with MATLAB; cardiac, muscle and brain physiology; and cellular electrophysiology.

**EN.580.637. Microphysiological Systems. 3 Credits.**

This course focuses on the principle and application of biological and engineering fundamentals to design microphysiological systems such as organ/tissue chips, 3D-printed tissues, and organoids. This course will introduce the concept of human organ-on-a-chip and organoid engineering and discuss the latest developments in the field of drug development - the shift from animal testing toward human relevant, high content, high-throughput integrative testing strategies. Students will learn various biofabrication techniques such as microfluidics, microfabrication, and 3D bioprinting to create in vitro miniaturized 3D complex human tissue models that mimic the biochemical, electrical, and mechanical properties of organ or tissue function. This course will also cover a wide range of biomedical applications of microphysiological systems in disease modeling, drug screening, precision medicine, and space biology as well as technology commercialization efforts. This laboratory portion of the course consists of three experiments that will provide students with valuable hands-on experience in design, fabrication and applications of microphysiological systems, including organ-on-a-chip systems (tissue/organ chips), 3-D printed tissue constructs, and organoids. Experiments include 1) the basics of human induced pluripotent stem cell differentiation, 2) tissue/organ chip fabrication, and 3) functional phenotypic analysis and drug testing. Spring semester only. Recommended background: EN.580.441, EN.580.442 and EN.580.452  
Area: Engineering

**EN.580.638. Biomedical Data Design II. 4 Credits.**

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

**EN.580.639. Models of the Neuron. 4 Credits.**

Single-neuron modeling, emphasizing the use of computational models as links between the properties of neurons at several levels of detail. Topics include thermodynamics of ion flow in aqueous environments, biology and biophysics of ion channels, gating, nonlinear dynamics as a way of studying the collective properties of channels in a membrane, synaptic transmission, integration of electrical activity in multi-compartment dendritic tree models, and properties of neural networks. Students will study the properties of computational models of neurons; graduate students will develop a neuron model using data from the literature. Differs in that an advanced modeling project using data from the literature is required. Graduate version of EN.580.439. Recommended Course Background: AS.110.302 or equivalent.

**EN.580.640. Systems Pharmacology and Personalized Medicine. 4 Credits.**

We have moved beyond the 'one-size-fits-all' era of medicine. Individuals are different, their diseases are different, and their responses to drugs are different too. This variability is not just from person to person; heterogeneity is observed even between tumors within the same person, and between sites within the same tumor. These levels of variability among the human population must be accounted for to improve patient outcomes and the efficiency of clinical trials. Some of the ways in which this is being explored include: drugs are being developed hand-in-hand with the tests needed to determine whether or not they will be effective; tumor fragments excised from patients are being cultured in the lab for high-throughput testing of drugs and drug combinations; data-rich assays such as genomics and proteomics identify thousands of potentially significant differences between individuals; and computational models are being used to predict which therapies will work for which patients. This course will focus on the applications of pharmacokinetics and pharmacodynamics to simulating the effects of various drugs across a heterogeneous population of diseased individuals. Such computational approaches are needed to harness and leverage the vast amounts of data and provide insight into the key differences that determine drug responsiveness. These approaches can also explore the temporal dynamics of disease and treatment, and enable the modification of treatment during recovery. Recommended background: 110.201 Linear Algebra, 110.302 Differential Equations, and 553.311 Probability and Statistics (or equivalent).

**EN.580.641. Cellular Engineering. 4 Credits.**

This course focuses on principles and applications in cell engineering. Class lectures include an overview of molecular biology fundamentals, protein/ligand binding, receptor/ligand trafficking, cell-cell interactions, cell-matrix interactions, and cell adhesion and migration at both theoretical and experimental levels. Lectures will cover the effects of physical (e.g. shear stress, strain), chemical (e.g. cytokines, growth factors) and electrical stimuli on cell function, emphasizing topics on gene regulation and signal transduction processes. Furthermore, topics in metabolic engineering, enzyme evolution, polymeric biomaterials, and drug and gene delivery will be discussed. This course meets with EN.580.441 but includes additional requirements designed for the core curriculum of the RIE (Regenerative and Immune Engineering) track of the BME masters program. The course is also appropriate for Cell & Tissue Engineering Ph.D. students and may be taken by advanced undergraduate students upon permission of the instructor. Prerequisites: Graduate standing with background in cell biology and biochemistry or EN.580.221 or AS20.305 and AS.020.306 (or equivalent) and AS.030.205 or permission of the instructor.

**EN.580.642. Tissue Engineering. 3 Credits.**

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

**EN.580.643. Advanced Orthopaedic Tissue Engineering. 3 Credits.**

This course is intended to provide a comprehensive overview on the current state of the field of Orthopaedic Tissue Engineering. Students will apply engineering fundamentals learned in the Tissue Engineering course (580.442/580.642) with special emphasis on how they apply to bone, cartilage, and skeletal muscle tissue engineering. The development, structure, mechanics, and function of each of these tissues will be discussed. Key articles from the last three decades that focus on stem cell- and cell-free, biomaterial-based approaches to regenerate functional tissues will be presented and analyzed. Practical (regulatory/commercial) considerations that restrict the translation of therapies to the clinic will be discussed. Undergraduate by permission only. Recommend Course Background: EN.580.442 or EN.580.642.

**EN.580.644. Biomedical Applications of Glycoengineering. 3 Credits.**

This course provides an overview of carbohydrate-based technologies in biotechnology and medicine. The course will begin by briefly covering basics of glycobiology and glycochemistry followed by detailed illustrative examples of biomedical applications of glycoengineering. A sample of these applications include the role of sugars in preventative medicine (e.g., for vaccine development and probiotics), tissue engineering (e.g., exploiting natural and engineered polysaccharides for creating tissue or organs de novo in the laboratory), regenerative medicine (e.g., for the treatment of arthritis or degenerative muscle disease), and therapy (e.g., cancer treatment). A major part of the course grade will be based on class participation with each student expected to provide a "journal club" presentation of a relevant paper as well as participate in a team-based project designed to address a current unmet clinical need that could be fulfilled through a glycoengineering approach. Recommended Course Background: EN.580.221 Molecules and Cells or equivalent (molecular and cell biology), college level calculus and calculus-based general physics.

Area: Engineering, Natural Sciences

**EN.580.645. Business of Healthcare Innovation & Design II. 3 Credits.**

This course builds upon the introductory business course for graduate students at the Center for Bioengineering Innovation and Design (CBID) and introduces students to several key topics relevant to translating an early-stage medical technology to the marketplace. Students will learn to assess and articulate the value proposition of their innovation, develop business models, and detailed business plans, including regulatory, reimbursement, IP, and overall market access strategy. Topics will be taught as a combination of lectures and hands-on workshops, with most of the content will be applied directly to the ongoing innovation projects at CBID as part of the course deliverables.

**EN.580.646. Molecular Immunoengineering. 3 Credits.**

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

Area: Engineering, Natural Sciences

**EN.580.647. Computational Stem Cell Biology. 3 Credits.**

This course will provide the student with a mechanistic and systems biology-based understanding of the two defining features of stem cells: multipotency and self-renewal. We will explore these concepts across several contexts and perspectives, emphasizing seminal and new studies in development and stem cell biology, and the critical role that computational approaches have played. The course will start with an introduction to stem cells and a tutorial covering computational basics. The biological contexts that we will cover thereafter include "Cell Identity", "Pluripotency and multipotency", "Stem cells and their niche", "Modeling cell fate decisions", and "Engineering cell fate". This class is heavily weighted by individual computational assignments. The motivation for this strategy is that regularly occurring, moderately-sized computational projects are the most efficient way to impart an understanding of our models of this extraordinary class of cells, and to inspire a sense of excitement and empowerment. Preferred background: 580.221 Molecules and Cells or equivalent and familiarity with the UNIX shell.

**Prerequisite(s):** Students may earn credit for EN.580.447 or EN.580.647, but not both.

Area: Engineering, Natural Sciences

**EN.580.656. Introduction to Rehabilitation Engineering. 3 Credits.**

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

Area: Engineering

**EN.580.658. Computing the Transcriptome. 3 Credits.**

This course will introduce computational tools used in the field of transcriptomics to analyze the genes and transcripts expressed in a living cell. Lectures will cover different practical ways to analyze large data sets generated by high-throughput RNA sequencing (RNA-Seq) experiments, including alignment, assembly, and quantification. The students will learn how to use RNA-seq to answer questions such as: what is the complete set of human genes? How do we reconstruct the splice variants that are transcribed in different cell types and conditions? How do we compute which genes are differentially expressed between different RNA-seq datasets? Prerequisites: (1) Familiarity with Python or Perl, (2) the Unix command-line environment, and (3) a basic understanding of programming in R.

Area: Engineering

**EN.580.664. Advanced Data Science for Biomedical Engineering. 4 Credits.**

This course covers the basics of data science in biomedical engineering. The main topics include, introductory R, data cleaning, reproducible research, basic statistical inference, machine learning and artificial intelligence. Specific topics include: assessing diagnostic accuracy, basic probability, tidy data principles, prediction and data oriented web-app development using R/shiny. Students taking the course will learn a complete and practical pipeline of going from raw data to a data product. Suggest course background: proficiency in basic programming in at least one language, basic calculus, and linear algebra.

**EN.580.668. Practical Human Neuroimaging. 3 Credits.**

Neuroimaging is widely used in basic research and clinical practice. This course will introduce the basic principles of magnetic resonance imaging (MRI) and provide students with hands-on experience manipulating, analyzing, and interpreting MRI data sets. We will focus on four types of MRI used to understand human neuroscience: structural imaging, functional imaging, diffusion imaging, and perfusion imaging. After taking this course students will have a practical understanding of working with a variety of MRI data sets. Recommended background: Linear Algebra and programming experience (Python, Matlab, or C).

Area: Engineering

**EN.580.674. Introduction to Neuro-Image Processing. 3 Credits.**

Developments in medical image acquisition systems such as magnetic resonance imaging (MRI) and computed tomography (CT) have resulted in large number of clinical images with rich information regarding structure and function of nervous system. A challenging task is to extract clinically relevant information from the raw images that can be used to characterize structural alteration of brain in disease state. This course introduces the underlying physical foundation of different image modalities that are used to study neurological disorders followed by presentation of concepts and techniques that are used to process and extract information from medical images, in particular MRI. Topics that are covered include medical image formats, enhancement, segmentation, registration, and visualization. Suggest Course Background: Mathematical Methods For Engineers or equivalent course, Signals and Systems, and Probability.

**EN.580.678. Biomedical Photonics I. 4 Credits.**

This course will cover the basic optics principles including geometric, beam and wave description of light. The course will also cover the basic generation and detection techniques of light and the principles of optical imaging and spectroscopy. After the basis is established, we will focus on some commonly employed optical techniques and tools for biomedical research including various optical microscopy technologies, fiber optics, Raman spectroscopy, Fluorescence (lifetime), FRAT, FRET and FCS.

The recent development in tissue optics, biomedical optical imaging/spectroscopy techniques (such as OCT, multiphoton fluorescence and harmonics microscopy, Structured Illumination, light scattering, diffuse light imaging and spectroscopy, optical molecular imaging, photo-acoustic imaging) will also be discussed. Representative biomedical applications of translational biomedical photonics technologies will be integrated into the corresponding chapters.

**Prerequisite(s):** Students must have completed Lab Safety training prior to registering for this class. To access the tutorial, login to myLearning and enter 458083 in the Search box to locate the appropriate module.

Area: Engineering

**EN.580.679. Principles and Applications of Modern X-ray Imaging and Computed Tomography. 3 Credits.**

This course provides students with an intermediate-level understanding of the physics, engineering, algorithms, and applications (clinical, pre-clinical, and industrial) of x-ray imaging and computed tomography (CT). It is intended for senior undergraduates (EN.580.479) and/or graduate students (EN.580.679) in Biomedical Engineering, Computer Science, Electrical and Computer Engineering, or related fields in science and engineering. Topics include the physics of x-ray interaction and detection, image quality assessment, 3D image reconstruction (including analytical, iterative, and deep-learning approaches), and quantitative image data analysis. Guest lectures from clinical experts introduce applications in diagnostic and image-guided procedures. The students conduct experimental and computational projects involving acquisition and processing of x-ray CT data. Recommended background: Signals and Systems or an equivalent course and familiarity with Matlab.

Area: Engineering

**EN.580.680. Precision Care Medicine. 4 Credits.**

Precision Care Medicine is a two-semester project-based learning course. Projects will use methods of machine learning and mechanistic and statistical modeling to develop novel data-driven solutions to important health care problems that arise in various areas of medicine including critical care medicine. The scope of such problems is vast and solutions can improve the delivery of patient care. Examples include data- and modeling-driven approaches to: optimal selection of patients to be admitted to ICUs; optimal determination of when it is safe to discharge a patient from an ICU; early prediction of pending changes in the clinical state of patients in an ICU; data-driven optimal selection of patient therapy; and others. In the first semester, students will assemble into teams of 5-6, and will work with their project mentors (clinical faculty in Johns Hopkins Medicine; Drs. Greenstein and Taylor) to develop a project work plan. In the remainder of the course, students will apply engineering approaches to solve the important health care problems in their projects. Class time will include: lectures and tutorials covering the physiology, medicine, and engineering principles relevant to each project; project work in a setting where faculty are available to assist students with challenges. HIPAA regulations and use of human subjects data will be covered. Each team will present project updates to the entire class at regular intervals so that every student becomes familiar with each project. Teams will be charged with designing, validating and deploying their model and an application that delivers the computational method for solving the underlying healthcare problem to the user. The goal is to generate results and one or more manuscripts to be submitted for publication by the end of the second semester.

**EN.580.681. Precision Care Medicine. 3 Credits.**

Precision Care Medicine is a two-semester project-based learning course. Projects will use methods of machine learning and mechanistic and statistical modeling to develop novel data-driven solutions to important health care problems that arise in anesthesiology and critical care medicine. The scope of such problems is vast, and few have been approached before. Examples include data- and modeling-driven approaches to: optimal selection of patients to be admitted to ICUs; optimal determination of when it is safe to discharge a patient from an ICU; early prediction of pending changes in the clinical state of patients in an ICU; data-driven optimal selection of patient therapy; and others. In the first semester, students will assemble into teams of 3-4, and will work with their project mentors (clinical faculty in the ACCM Department; Drs. Winslow and Sarma) to develop a project work plan. In the remainder of the course, they will apply engineering approaches to solve the important health care problems in their projects. Class time will include: lectures and tutorials covering the physiology, medicine, and engineering principles relevant to each project; project work in a setting where faculty are available to assist students with challenges. Each team will present project updates to the entire class at regular intervals so that every student becomes familiar with each project. Teams will also be charged with designing, validating and deploying a web-application that delivers the computational method for solving the underlying healthcare problem to the user. HIPAA regulations, use of human subjects data, and requirements for FDA Class II and Medical Device Data Systems approval will be covered.

**Prerequisite(s):** EN.580.480 OR EN.580.680

**EN.580.682. Precision Care Medicine III. 3 Credits.**

Precision Care Medicine III follows Precision Care Medicine I - II. Registration is open only to those students who have completed these courses and who wish to continue project course work under the mentorship of the Biomedical and Engineering PIs. Students will have regular meetings with their PIs.

**EN.580.683. Annotate a Genome. 3 Credits.**

The course will present practical and specific understanding of approaches for genome interpretation. Topics will include Common Variants, Rare and Novel Variants, Personal Genomics and the Environment, Ethical considerations in personal genomics, Structural Variation, Pharmacogenetic variants, and Genetic Trait Associations. Students will learn bioinformatic methods to predict the impact of variants and to rapidly pull published information about variants identified in a genome. Students will work in teams to do exercises and programming projects on personal genomics datasets. Recommended Background: prior coursework in Genetics, Intermediate Programming  
Area: Quantitative and Mathematical Sciences

**EN.580.688. Foundations of Computational Biology and Bioinformatics. 3 Credits.**

This course will introduce probabilistic modeling and information theory applied to biological sequence analysis, focusing on statistical models of protein families, alignment algorithms, and models of evolution. Topics will include probability theory, score matrices, hidden Markov models, maximum likelihood, expectation maximization and dynamic programming algorithms. Homework assignments will require programming in Python. Recommended Course Background: Math through linear algebra and differential equations, EN.580.221 or equivalent, EN.601.226 or equivalent.

**EN.580.689. Modern Optical Microscopy: Theory and Practice. 3 Credits.**

This course will teach the fundamental theory in optical microscopy, including propagation of electromagnetic wave, and Fourier optic. The course will also teach how the theoretical framework is practiced and applied in modern microscopy, by in-class demonstration and hands-on lab projects. Background knowledge: Fourier transform, linear algebra.

**Prerequisite(s):** Students may only earn credit for EN.580.489 or EN.580.689.

Area: Engineering

**EN.580.691. Learning, Estimation and Control. 3 Credits.**

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

**EN.580.693. Imaging Instrumentation. 4 Credits.**

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

**Prerequisite(s):** Students must have completed Lab Safety training prior to registering for this class. To access the tutorial, login to myLearning and enter 458083 in the Search box to locate the appropriate module.

**EN.580.697. Biomedical Data Design. 4 Credits.**

In this year long course, students will work together in small teams to design, develop, and deploy a functioning tool for practicing biomedical scientists, either for accelerating research or augmenting the clinic. The first semester will focus on scoping the tool, including determining feasibility (for us in a year) and significance (for the targeted brain science community), as well as a statement of work specifying deliverables and milestones. The second semester will focus on developing the tool, getting regular feedback, and iterating, using the agile/lean development process. Recommended Course Background: linear algebra, probability and statistics, numerical programming.

**EN.580.701. CBID Masters Advanced Project. 3 - 10 Credits.**

For second year CBID students.

**EN.580.702. CBID Masters Advanced Project. 3 - 10 Credits.**

Project work for second year CBID students only.

**EN.580.709. Sparse Representations in Computer Vision and Machine Learning. 3 Credits.**

Sparse and redundant representations constitutes a fascinating area of research in signal and image processing. This is a relatively young field that has been taking form for the last 15 years or so, with contributions from harmonic analysis, numerical algorithms and machine learning, and has been vastly applied to myriad of problems in computer vision and other domains. This course will focus on sparsity as a model for general data, generalizing many different other constructions or priors. This idea - that signals can be represented with just "a few" coefficients - leads to a long series of beautiful (and surprisingly, solvable) theoretical and numerical problems, and many applications that can benefit directly from the new developed theory. In this course we will survey this field, starting with the theoretical foundations, and systematically covering the knowledge that has been gathered in the past years. This course will touch on theory, numerical algorithms, and applications in image processing and machine learning. Recommended course background: Linear Algebra, Signals and Systems, Numerical Analysis.

**EN.580.710. Ethical Challenges in Biomedical Engineering. 2 Credits.**

This course will address the mores of scholarship and responsible practices in conducting biomedical research. Discussions will be focused on the grey areas encountered in considering and determining the best conduct for performing biomedical research and will emphasize how decisions depend on multiple factors and contexts. Issues to be discussed will span the main focus areas in the Biomedical Engineering Department: Cell and Tissue Engineering, Imaging, Genomics, Computational Medicine, Biomedical Data Science, and Neuroscience. Each week a short lecture will be presented by a faculty member, followed by breakdown into small groups for discussion and debate. Course restricted to BME PhD Students Only.

**EN.580.711. Quantitative Methods in BME. 1 Credit.**

This course is designed to introduce students to the diverse quantitative approaches that are used to tackle BME research and design questions. It allows students to identify areas of interest by exposing them to quantitative methods that they had not been exposed to and also to identify connections between on the surface disparate areas of BME. The topics range from methods used in bioinformatics, neuroengineering, immunoengineering, imaging, and cell and tissue engineering.

**EN.580.720. Immunomodulatory Biomaterials: Design, Synthesis, and Applications. 3 Credits.**

The objective of this course is to teach students the chemistry, immunology, and materials engineering fundamentals necessary to develop novel materials that modulate immune responses for the treatment and prevention of diseases. This course will present many of the small molecule and polymer chemistry strategies used to synthesize state-of-the-art biomaterials. The concepts of spatio-temporal delivery of therapeutics, biomaterials degradation, biocompatibility, and various structure-function relationships between biomaterials and the immune system will be introduced. The role played by adaptive and innate immunity in the development and persistence of cancer, infectious diseases, and autoimmunity will be explored. Emphasis will be placed on the design elements that have been, and could be, engineered into immunomodulatory materials to improve human health outcomes. Recommended background: Organic Chemistry I

Area: Engineering, Natural Sciences

**EN.580.723. Introduction to MRI in Medicine. 3 Credits.**

Advances in magnetic resonance Imaging (MRI) have resulted in developing techniques such as diffusion imaging, delayed contrast enhanced imaging, tagged, flow map and many other imaging contrasts. These techniques offer insights into the structure and function of brain and other anatomical regions in the body. With increased availability of these techniques in clinical MRI machines, they are now entering clinical practice for the evaluation of disease. This course presents the underlying physical foundation of MRI, with a focus on more advanced techniques and their application in clinical research and practice. Topics that are covered include foundations of MRI (signal detection and construction, image contrast), diffusion weighted imaging, and cardiac imaging. Attention is also drawn to possible artifacts and pitfalls. Suggested course background: Signals and systems/multi-dimensional digital signal processing, differential equations, linear algebra.

**EN.580.725. Radiology for Engineers. 3 Credits.**

This course provides engineering students with an introductory understanding of the principles and practice of radiology – including a spectrum of specialties in diagnostic radiology as well as procedures in interventional radiology and digital pathology. The course includes lectures, working with real image data, and visits to clinical areas at Johns Hopkins Hospital. Each segment of the course emphasizes clinical perspective on imaging (including scanner technology and image analysis) in relation to anatomy, physiology, and pathology. Each segment is led by an expert in a particular discipline in collaboration with the course director. Recommended course background: 580.472, 601.455 Restricted to BME MSE and BME PhD students only. Others by instructor permission. Audits are not allowed. Area: Engineering, Natural Sciences

**EN.580.735. Advanced Seminars in Computational Medicine. 1 Credit.**

In this course, students will review current literature on the most salient and interesting topics in the emerging field of Computational Medicine, which is focused on the development of quantitative approaches for understanding the mechanisms, diagnosis and treatment of human disease through applications of mathematics, engineering, and computational science. Whenever possible, the publications considered will be directly relevant to the lectures delivered by visiting scholars in the Institute for Computational Medicine's seminar series. Students will be required to search for the most relevant papers in the current literature; read and critically interpret these papers; conduct interactive teaching sessions with the course instructor, other students, and trainees/faculty from the Institute. Potential topics will include: computational anatomy; computational molecular medicine; computational physiological medicine; and computational healthcare. Evaluation will be by the course instructor (pass/fail). Graduate level. Seniors by permission. All registrants must be approved by the course instructor.

**EN.580.736. Distinguished Seminar Series in Computational Medicine. 1 Credit.**

Over the past ten years, extraordinary advances in modeling and computing technologies have opened the door to an array of possibilities that were previously beyond the reach of biomedical researchers. The next step, then, is to harness the potential of these theoretical and computational tools and theory in a meaningful way -that is, to apply this "new medicine" to the exploration and treatment of many of our current diseases. This course will require students to attend seminars hosted by JHU's Institute for Computational Medicine (ICM) once a month in addition to weekly discussions of recent scholarly advances in computational medicine and conversations with invited seminar speakers. Seminars are hosted on the first Tuesday of each month at 4:00 pm.

**EN.580.737. Distinguished Seminar Series in Computational Medicine. 1 Credit.**

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

**EN.580.740. Surgery for Engineers. 3 Credits.**

This course provides an introduction to basic principles and emerging techniques in surgery, interventional radiology, and radiation therapy for engineering students. Basic principles include introduction to fundamental surgical approaches and tools as well as sub-specialties, including neurosurgery, orthopaedic surgery, ENT surgery, thoracic surgery, and laparoscopic surgery as well as minimally invasive (body and neurovascular) interventional radiology as well as radiotherapy (external beam and brachytherapy). Introduction to cutting edge and emerging technologies include intraoperative imaging (all modalities), surgical navigation, and robotics. Prerequisite background for engineering students includes analytic geometry, linear algebra, computing (Matlab, Python, or C++), and basic familiarity with the physics of medical imaging. Safety Training: certificate in Bloodborne Pathogens and HIPAA & Research. Recommended course background: 580.472, 601.455

**EN.580.742. Neural Implants and Interfaces. 3 Credits.**

This course will focus on invasive neural implants that electrically interface with the peripheral or central nervous system. We will investigate the different types of recording and stimulating neural interface technologies currently in use in patients as well as coverage of the biophysics, neural coding, and hardware. We will also cover computational modeling of neurophysiology in the context of implantable devices and their neural interfaces. A final group project will be required for simulating a neural interface system. Class material assumes strong familiarity with the following topics: cell biology, physics with electromagnetics (or electrical circuits), chemistry, differential equations. Computer programming experience is required: all assignments include Matlab programming.

**EN.580.743. Advanced Topics in Genomic Data Analysis. 3 Credits.**

Genomic data is becoming available in large quantities, but understanding how genetics contributes to human disease and other traits remains a major challenge. Machine learning and statistical approaches allow us to automatically analyze and combine genomic data, build predictive models, and identify genetic elements important to disease and cellular processes. This course will cover current uses of statistical methods and machine learning in diverse genomic applications including new genomic technologies. Students will present and discuss current literature. Topics include personal genomics, integrating diverse genomic data types, new technologies such as single cell sequencing and CRISPR, and other topics guided by student interest. The course will include a project component with the opportunity to explore publicly available genomic data. Recommended Course Background: coursework in data science or machine learning.

**EN.580.745. Mathematics of Deep Learning. 1.5 Credits.**

The past few years have seen a dramatic increase in the performance of recognition systems thanks to the introduction of deep networks for representation learning. However, the mathematical reasons for this success remain elusive. For example, a key issue is that the training problem is nonconvex, hence optimization algorithms are not guaranteed to return a global minima. Another key issue is that while the size of deep networks is very large relative to the number of training examples, deep networks appear to generalize very well to unseen examples and new tasks. This course will overview recent work on the theory of deep learning that aims to understand the interplay between architecture design, regularization, generalization, and optimality properties of deep networks. Recommended background: machine learning (EN.601.475), deep learning (EN.520.438 or EN.601.482), graduate-level matrix analysis and linear algebra (EN.553.792) and graduate-level optimization (EN.553.762).

**EN.580.746. Imaging Science Seminar. 1 Credit.**

Fall semester only.

**EN.580.747. Imaging Science Seminar. 1 Credit.**

In this seminar course, students will review current literature on the most salient and interesting topics in the fields of Imaging and Data Science through a series of invited talks by leading experts, from foundational ideas to exciting applications. This course is held concurrently to the seminar series of the Center for Imaging Science (CIS) and the Mathematical Institute for Data Science (MINDS). More information will be periodically updated and posted at the CIS and MINDS websites. Graduate level. Seniors by permission.

**EN.580.750. Surgineering: Systems Engineering and Data Science in Interventional Medicine. 3 Credits.**

This course provides engineering students with deep clinical immersion in interventional medicine complemented by instruction in systems engineering and data science pertaining to medical technology, information, and workflow. The course involves one-to-one matching of students with Clinical Mentors, who oversee the students' clinical immersion and involvement on clinical teams. Weekly class meetings with visitation by one or more of the Clinical Mentors focus on principles of systems engineering and data science as well as journal articles on emerging topics in technology and information science in interventional medicine. Each student completes a course project that addresses a particular question or challenge in technology integration, data-flow, workflow, patient safety, and quality assurance in one of the clinical areas covered in the course. Prerequisites and Certificates Prerequisite for the course is 580.740 (Surgery for Engineers), which introduces principles and practice of interventional medicine – including open and minimally invasive surgical approaches as well as interventional radiology and radiation oncology. Students must provide a copy of the following certifications, each available as Hopkins myLearning modules at myJHU: • Bloodborne Pathogens • Fluoroscopy Refresher • Patient Privacy for Workforce Members

**EN.580.752. Advanced Topics in Regenerative and Immune Engineering. 4 Credits.**

This course is designed as part of the core curriculum for the RIE track for the BME masters program. Topics will be selected based on current methods, basic research, and clinical translation of regenerative medicine and immune engineering technologies. Background Knowledge: EN.580.641, EN.580.642, and EN.580.751 or graduate standing and permission of the instructor.

**EN.580.753. Cell and Tissue Engineering Lab Advanced Project. 1 Credit.**

This one credit laboratory course provides students with the opportunity to obtain experience in advanced project design and implementation in conjunction with the graduate-level Cell & Tissue Laboratory course (EN.580.754). It is appropriate for students who have previously taken the undergraduate version of this course to fulfill the core curriculum requirement of the RIE (Regenerative and Immune Engineering) track of the BME master's program. Graduate students may also take this course with permission of the instructor to pursue additional 'advanced topics' laboratory modules. The work will be completed over the course of the semester in conjunction with the "advanced topics" component of the regular graduate level version of the lab course.

**EN.580.754. Cell & Tissue Engineering Lab. 4 Credits.**

This flipped-content laboratory course will consist of modules that provide students with valuable hands-on experience in cell and tissue engineering. Modules contain experiments including the basics of cell culture techniques, gene transfection, metabolic glycoengineering, and cell encapsulation. Students will collect and analyze their own experimental data, write-up results in publication structured reports, and engage in active discussion of current scientific literature. An independent group project based in cellular engineering principles will be designed and presented by the students as a capstone for the course. Students who previously completed 580.452 Cell & Tissue Engineering Lab may NOT register for this class. Textbook Info None. Prerequisites Students must have completed the online "Introductory Laboratory Safety" and "Bloodborne Pathogens" prior to registering for this class. To access these courses, log in to MyLearning and identify these tutorials.

**EN.580.771. Principles of the Design of Biomedical Instrumentation. 4 Credits.**

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

**Prerequisite(s):** Students must have completed Lab Safety training prior to registering for this class. To access the tutorial, login to myLearning and enter 458083 in the Search box to locate the appropriate module.

**EN.580.781. Biomedical Engineering Seminar. 1 Credit.**

In this course, scientists from other institutions present cutting edge research that is relevant to biomedical engineering. Each session takes 1 hour for the seminar together with Q&A.

**EN.580.782. Biomedical Engineering Seminar. 1 Credit.**

In this course, scientists from other institutions present cutting edge research that is relevant to biomedical engineering. Each session takes 1 hour for the seminar together with Q&A.

**EN.580.788. Biomedical Photonics II. 4 Credits.**

This course serves as the continuation of 580.678 (520.678), Biomedical Photonics I. It will cover the advanced topics on biomedical photonics, including, but not limited to, light scattering (Rayleigh and Mie scattering), photon diffusion, polarization (birefringence), fluorescence, lifetime measurements, confocal microscopy, optical coherence tomography, nonlinear microscopy, and super-resolution microscopy. Representative biomedical applications of some of these technologies will be integrated into the relevant chapters. A hand-on lab section (optional) for students to design and build an imaging instrument, space permitting. No Audits.

**EN.580.801. Research in Biomedical Engineering. 3 - 10 Credits.**  
Graduate Students only

**EN.580.802. Research in Biomedical Engineering. 1 - 10 Credits.**  
Directed research for MSE and PhD students

**EN.580.803. Research in Biomedical Engineering. 3 - 10 Credits.**  
Course is for students conducting research for credit. P/F grading only

**EN.580.805. BME MSE Independent Study. 1 Credit.**  
Independent Study

**EN.580.806. CBID Summer Research. 9 Credits.**  
Independent project work for second year CBID students only.

**EN.580.812. Biomedical Graduate Research. 9 Credits.**  
Student participation in on-going research activities. Research is conducted under the supervision of a BME faculty member.

**EN.580.821. Applied Research and Grant Methodology. 3 Credits.**

The goal of this course is to guide a student through the process of designing a scientific project as well as evaluating others' projects (i.e., providing "peer review"). Course requirements include attending lectures describing successive stage of project design; providing iterative oral and written reports on your own research proposal/project; as well providing feedback on your colleagues' (i.e., your fellow students in the class) projects and proposals. A final research proposal to be presented in the format of a NIH-style grant application will provide evidence that a student is capable of designing an advanced research project by identifying a significant biomedical problem, developing innovative approaches to solve it, and then designing a practical, relevant, and implementable research plan. This course is often taken in conjunction with – and based upon – an independent project being done by the student in a research laboratory but students without a laboratory position are welcome to take this course based on a hypothetical research project of their choosing.

**Prerequisite(s):** EN.500.601

**EN.580.843. Independent Study: Advances in Immunoengineering. 2 Credits.**

This independent study will investigate the diverse and complex fields of engineering and immunology and how it is transforming patient treatment in cancer, autoimmunity, regeneration, and transplantation.

**EN.580.850. BME MSE Research Practicum. 6 Credits.**

BME MSE Research Practicum For Thesis-Track Students