Biomedical Engineering

Biomedical engineering (BME) seeks to advance and integrate life science knowledge with engineering methods and innovations that contribute to improvements in human health and well-being. Our vision is that lasting knowledge of biomedical systems and paradigm-shifting engineering technology will arise from integrating engineering concepts and basic science knowledge from the molecular level to the whole-body level. We believe that those taught to work across multiple disciplines and to integrate modeling and experimental systems approaches will be uniquely positioned to advance and generate new disciplines in biomedical engineering.

With this vision in mind, we are committed to educating the next generation of biomedical engineers. We have leveraged our interdisciplinary strengths in engineering and clinical and life sciences to build a biomedical engineering department around research programs of excellence and translational potential: Biomedical & Biological Imaging; Cardiovascular Engineering; Cellular & Molecular Bioengineering; Neural Engineering; Orthopedic Engineering; Regenerative Engineering in Medicine; and Women's Health Technologies. These areas provide exciting opportunities for students with a variety of backgrounds and interests.

Students seeking the Master of Science (MS) in Biomedical Engineering will need to complete 30 course credits, which include a core curriculum. MS students pursuing the thesis option perform research on a topic approved by the research mentor. Results of the study are published in a thesis that is defended in front of a committee of faculty members prior to graduation. The results should be of quality high enough to be published as a paper in a peer-reviewed journal. A total of 30 credits can be completed in two to four semesters.

Students seeking the PhD in Biomedical Engineering may choose to study in one of seven multidisciplinary research programs that represent frontiers in biomedical engineering. Our core faculty work collaboratively with more than 90 affiliated faculty to offer students the opportunity to learn in a diverse and rich spectrum of BME research areas. Students graduating with the PhD in Biomedical Engineering are prepared to pursue paths in research and development in academic and industry settings, and they are also ready to contribute to teaching and research translation. The MD/PhD in Biomedical Engineering, which is offered jointly with the top-ranked School of Medicine, gives students in-depth training in modern biomedical research and clinical medicine. The typical MD/PhD career combines patient care and biomedical research but leans toward research.

Endowed Professors

Rohit V. Pappu
Edwin H. Murty Professor of Engineering
PhD, Tufts University
Macromolecular self assembly and function; computational biophysics

Yoram Rudy
Fred Saigh Distinguished Professor of Engineering
PhD, Case Western Reserve University
Cardiac electrophysiology; modeling of the cardiac system

Professors

Jianmin Cui
PhD, State University of New York–Stony Brook
Ion channels; channel structure-function relationship; biophysics

Daniel Moran
PhD, Arizona State University
Motor control; neural engineering; neuroprosthetics; movement biomechanics

Baranidharan Raman
PhD, Texas A&M University
Computational and systems neuroscience; neuromorphic engineering; pattern recognition; sensor-based machine olfaction

Quing Zhu
PhD, University of Pennsylvania
Biophotonics and multimodality ultrasound and optical imaging

Email: bme@wustl.edu
Website: https://bme.wustl.edu/academics/graduate-programs/index.html

Faculty

Chair
Lori A. Setton
Lucy and Stanley Lopata Distinguished Professor of Biomedical Engineering
PhD, Columbia University
Biomaterials for local drug delivery; tissue regenerations specific to the knee joints and spine

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Quing Zhu
PhD, University of Pennsylvania
Biophotonics and multimodality ultrasound and optical imaging
**Associate Professors**

Dennis L. Barbour (https://engineering.wustl.edu/faculty/Dennis-Barbour.html)
MD, PhD, Johns Hopkins University
Application of novel machine learning tools to diagnose and treat disorders of perception and cognition

Hong Chen (https://engineering.wustl.edu/faculty/Hong-Chen.html)
PhD, University of Washington
Physical acoustics; therapeutic ultrasound and ultrasound imaging

Song Hu (https://engineering.wustl.edu/faculty/Song-Hu.html)
PhD, Washington University in St. Louis
Optical and photoacoustic technologies for high-resolution structural, functional, metabolic and molecular imaging in vivo

Princess Imoukhuede (https://engineering.wustl.edu/faculty/Princess-Imoukhuede.html)
PhD, California Institute of Technology
Ligand-receptor signal transduction; angiogenesis; computational systems bioengineering

PhD, Duke University
Cell mechanics; receptor and ligand interactions; molecular biomechanics

PhD, Washington University
Ion channel biophysics

Kurt A. Thoroughman (https://engineering.wustl.edu/faculty/Kurt-Thoroughman.html)
PhD, Johns Hopkins University
Human motor control and motor learning; neural computation

Chao Zhou
PhD, University of Pennsylvania
Optical coherence tomography

**Assistant Professors**

Nate Huebsch (https://engineering.wustl.edu/faculty/Nathaniel-Huebsch.html)
PhD, Harvard University
Cell-material Interactions, iPSC-based tissue modeling to study cardiac development and disease

Abhinav Kumar Jha (https://engineering.wustl.edu/faculty/Abhinav-Jha.html)
PhD, University of Arizona
Development of computational-imaging solutions for diagnosing and treating diseases

PhD, Louisiana Tech University
Peptide-based biomaterials; immunoengineering; immunology of nanoscale aggregates; development of vaccines and immunotherapies

Alexandra Rutz (https://engineering.wustl.edu/faculty/Alexandra-Rutz.html)
PhD, Northwestern University
Engineering of electronic tissues using materials design and fabrication-based approaches

Ismael Seáñez (https://engineering.wustl.edu/faculty/Ismael-Seanez.html)
PhD, California Institute of Technology
Neuro-rehabilitation tools and programs that promote active use of residual mobility and maximize recovery through the use of body-machine interfaces

Michael D. Vahey (https://engineering.wustl.edu/faculty/Michael-Vahey.html)
PhD, Massachusetts Institute of Technology
Biophysical mechanisms of infectious disease; fluorescence microscopy; microfluidics

**Principal Lecturer**

Patricia Widder (https://engineering.wustl.edu/faculty/Patricia-Widder.html)
MS, Washington University

**Lecturer**

Katherine Schreiber
PhD, Saint Louis University

**Senior Professor**

Larry Taber
PhD, Stanford University
Mechanics of growth and development; cardiac mechanics

**Senior Emeritus Professor**

Frank Yin
MD, PhD, University of California, San Diego

**Degree Requirements**

Please visit the following pages for information about our graduate programs:

- PhD and Combined MD/PhD in Biomedical Engineering (http://bulletin.wustl.edu/grad/engineering/biomedical/md-phd-biomedical/)
- Master of Science (MS) in Biomedical Engineering (http://bulletin.wustl.edu/grad/engineering/biomedical/ms-biomedical/)
Courses

Below are all BME graduate-level courses. Visit online course listings to view semester offerings for E62 BME (https://courses.wustl.edu/CourseInfo.aspx?sch=E&dept=E62&crs=V=5:8).

### E62 BME 501C BME Doctoral Seminar Series
This is a credit option for BME students who attend regularly scheduled BME seminars (or approved substitute seminars). A satisfactory grade is obtained by submission of a two-page peer-reviewed paper written by one of the regularly scheduled BME seminar speakers whose seminar the student attended. Papers are to be submitted to the Graduate Student Administrator for review by the Director of Doctoral Studies. Prerequisite: Current BME student in the second year or beyond. Credit 1 unit.

### E62 BME 505 Professional and Personal Pathways to the PhD Program
This course is designed to guide PhD students as they embark on their first year in the Biomedical Engineering program. Topics include choosing a thesis lab and mentor, creating individual development plans, career exploration, and building mentor relationships through networking. Credit 1 unit.

### E62 BME 506 Seminar in Imaging Science and Engineering
This seminar course consists of a series of tutorial lectures on Imaging Science and Engineering with emphasis on applications of imaging technology. Students are exposed to a variety of imaging applications that vary depending on the semester, but may include multispectral remote sensing, astronomical imaging, microscopic imaging, ultrasound imaging, and tomographic imaging. Guest lecturers come from several parts of the university. This course is required of all students in the Imaging Science and Engineering program; the only requirement is attendance. This course is graded pass/fail. Prerequisite: admission to Imaging Science and Engineering program. Same as E35 ESE 596 Credit 1 unit.

### E62 BME 507 Radiological Physics and Dosimetry
This class is designed to construct a theoretical foundation for ionizing radiation dose calculations and measurements in a medical context and prepare graduate students for proper scientific presentations in the field of x-ray imaging and radiation therapy. Specifically, a student completing this course will be able to do the following: 1. Understand and apply key concepts specific to energy deposition for both ionizing photon interactions and transport in matter and for energetic charged particle interactions and transport in matter. Radiation sources include radioactivity, x-ray tubes, and linear accelerators. 2. Understand the theoretical details of ion-chamber based dosimetry and of both cavity-theory based (TG-21) and Monte-Carlo based (TG-51) clinical protocols. 3. Perform and present real-world style research projects as a group, and present these projects in a typical professional scientific format and style. 4. Achieve an appreciation of the history and potential future developments in ionizing radiation detection and dosimetry. Prerequisites: BS in physics or engineering and instructor approval. Credit 3 units.

### E62 BME 5071 Radiobiology
Effects of ionizing radiations on living cells and organisms, including physical, chemical, and physiological bases of radiation cytotoxicity, mutagenicity and carcinogenesis. Textbook: Radiobiology for the Radiologist. Eric Hall and Amato Giaccia. Two lectures per week. Prerequisites: graduate student standing and one year each of biology, physics and organic chemistry, or approval of instructor. Credit 2 units.

### E62 BME 5072 Radiation Therapy Physics
Ionizing radiation use in radiation therapy to cause controlled biological effects in cancer patients. Physics of the interaction of the various radiation modalities with body-equivalent materials, and physical aspects of clinical applications. Lecture and lab. Prerequisites: graduate student standing or permission of instructor. Credit 3 units.

### E62 BME 5073 Radiation Protection and Safety
This course will introduce concepts of radiation protection and safety. The focus will be on how to protect humans and environment from ionizing radiation. Special emphasis will be on radiological protection in clinics. Prerequisite: graduate student standing or permission of the instructor. Credit 2 units.

### E62 BME 519 Advanced Cognitive, Computational, and Systems Neuroscience
This course will develop critical thinking and analysis skills with regard to topics in cognitive, computational and systems neuroscience. A particular focus of the course will be aimed toward quantitative literacy, statistical methodology, and pragmatic hands-on experience with the tools and best practices needed to conduct state-of-the-art research in modern studies of brain and behavior. Complementary approaches will be emphasized, including deduction vs. induction, frequentist vs. Bayesian, cohort vs. individual, and random vs. biased sampling. Particular topics include machine learning, Big Data, reproducibility, equitable research and scientific visualization. Students will be provided with foundational and theoretical tools to ensure maximal scientific rigor in their own research by enabling them to think carefully about core issues in experimental design and about key challenges and controversies that arise in relation to hypothesis testing, statistical inference and data management. Work will be conducted in MATLAB, R or Python, and prior experience with one of these tools is highly recommended. Prerequisite: Graduate standing or permission of instructor. Credit 3 units.

### E62 BME 523 Biomaterials Science
An understanding of the interactions between biological systems and artificial materials is of vital importance in the design of medical devices. This course will introduce the principles of biomaterials science, unifying knowledge from the fields of biology, materials science, surface science, and colloid science. The course will be taught from the primary scientific literature, focusing on the study of protein/surface interactions and hydrogel materials. Credit 3 units. EN: TU

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**Biomedical Engineering (08/31/21)**
**E62 BME 524 Tissue Engineering**

This course integrates the principles and methods of engineering and life sciences toward the fundamental understanding of normal and pathological mammalian tissues especially as they relate to the development of biological substitutes to restore or improve tissue function. Current concepts and strategies including drug delivery, tissue and cell transplantation, and in vivo tissue regeneration will be introduced as well as their respective clinical applications. Prerequisites: BME 366; or MEMS 3410, Biol 2960 and 2970; or permission of the instructor. Credit 3 units. EN: TU

**E62 BME 527 Design of Artificial Organs**

Medical devices that replace the function of one of the major organs in the body must usually interface with flowing blood. Examples include total artificial hearts, left ventricular assist devices, membrane oxygenators, hemodialysis systems and encapsulated endocrine cells. The design of these devices relies on integration of knowledge from a variety of fields, in particular computational fluid dynamics and blood rheology. We will study the process by which a concept for a device eventually leads to a functioning, blood-contacting medical device, with most of the focus on the design of left ventricular assist devices. Students will learn to use CAD to design blood pumping devices, test their designs via computational fluid dynamics, and 3D print and test their pumps with water. Prerequisites: BME 366 or equivalent course in transport phenomena (including momentum and mass transfer). Credit 3 units. EN: TU

**E62 BME 528 Translational Regenerative Medicine**

This course provides students with an opportunity to connect basic research with applications in translation for several tissues/disease models. Course sessions will alternate between literature on basic mechanisms of development/stem cell biology and applications led by researchers or clinicians working in each area. Areas of focus will include cardiovascular development/ congenital heart disease and arrhythmia, lung, endocrinology/ diabetes, gut/intestinal disorders, musculoskeletal, neural (peripheral and brain), liver, hematology and eye. Emphasis on how discovery can be translated will be a major focus of the course. Students will be expected to review and present on primary literature in the field. Graduate standing is required. Prerequisites: graduate standing Engineering or DBBS. Credit 3 units. EN: TU

**E62 BME 530A Molecular Cell Biology for Engineers**

This course is designed for upper-level undergraduates and first-year graduate students with a background in engineering. It covers the biology of cells of higher organisms: protein structure and function; cellular membranes and organelles; cell growth and oncogenic transformation; cellular transport, receptors, and cell signaling; and the cytoskeleton, the extracellular matrix, and cell movement. Emphasis will be placed on examples relevant to biomedical engineering. In addition to lecture material, a focus will be placed on understanding the experimental techniques used in cell biology and the critical analysis of primary literature. Note that this course does not count for engineering topics credits and that it is meant to fulfill a life science requirement for engineering or physical sciences graduate students. Prerequisites: Biol 2960 and Biol 2970 or graduate standing. Credit 3 units.

**E62 BME 532 Physics of Biopolymers and Bioinspired Polymers**

This course will cover physics concepts from the statistical physics of polymers and polymer solutions to describe proteins, nucleic acids, and bioinspired polymers. Topics include statistical physics concepts, theoretical and numerical descriptions of polymers, applying these descriptions to biopolymers, the thermodynamics of polymer solutions, concepts of polymer dynamics, descriptions of polymeric materials, and advanced topics in phase transitions and molecular design. The material will be fast paced and involve rigorous mathematical descriptions, experimental design, interpretations of experimental data, and some numerical simulations. The course will be heavy on individual homework and team-based project work. Direct connections between concepts and modern topics in biology and biomaterials will be emphasized. Prerequisites: BME 320B or equivalent and a first course in transport phenomena. Same as E62 BME 432 Credit 3 units. EN: TU

**E62 BME 533 Biomedical Signal Processing**

Course designed for graduate students with little or no background in signal processing. Continuous-time and discrete-time application of signal processing tools to a variety of biomedical problems. Course topics include review of linear signals and systems theory, frequency transforms, sampling theorem, basis functions, linear filtering, feature extraction, parameter estimation and biological system modeling. Special emphasis will be placed on signal transduction and data acquisition. Additional topics include noise analysis of real-world biosignals, biological system identification, stochastic/chaotic/fractal/nonlinear processes in biological systems. Concepts learned in class will be applied using software tools to 1D biomedical signals such as biological rhythms, chemical concentrations, blood pressure, speech, EMG, ECG, EEG. Prerequisites: graduate standing or consent of instructor. Credit 3 units. EN: TU

**E62 BME 537 Computational Molecular Biology**

This course is a survey of algorithms and mathematical methods in biological sequence analysis (with a strong emphasis on probabilistic methods) and systems biology. Sequence analysis topics include introduction to probability, probabilistic inference in missing data problems, hidden Markov models (HMMs), profile HMMs, sequence alignment, and identification of transcription-factor binding sites. Systems biology topics include discovery of gene regulatory networks, quantitative modeling of gene regulatory networks, synthetic biology, and (in some years) quantitative modeling of metabolism. Prerequisite: CSE 131 or CSE 501N. Same as E81 CSE 587A Credit 3 units. EN: BME T, TU

**E62 BME 538 Cell Signal Transduction**

This course will cover the elements of cell signal transduction important to human development, homeostasis and disease. Lectures will be combined with primary literature review to cover canonical signaling and current topics within the field. Spatial, time and dose-dependent aspects of signaling will be of particular focus. Topics include G protein-coupled receptors,
E62 BME 542 Biomacromolecules Design and Engineering
Biological macromolecules (i.e., carbohydrates, lipids, proteins, and nucleic acids) are important components of the cell and its supporting matrix that perform a wide array of functions. This course will introduce the principles and recent advances in nucleic acid/gene engineering, protein/peptide engineering, and chemical/enzymatic conjugation technologies; it will also discuss the application of engineered biomacromolecules in clinical therapeutics/diagnostics, biosensing, bioimaging, and biocatalysis. Students will learn material through lectures, reading, homework, scientific publications, and molecular visualization tools. Students will work individually or in pairs/groups to develop and lead discussions on engineering biomacromolecules and molecular characterization techniques. Prerequisite: Basic knowledge of genes and cloning. Same as E62 BME 442 Credit 3 units. EN: TU

E62 BME 543 Molecular and Cellular Engineering
This course aims to provide knowledge and practical proficiency in cellular and molecular vascular signaling in health and disease. Prerequisite: Biol 2960 and Math 217. Credit 3 units. EN: TU

E62 BME 544 Biomedical Instrumentation
This course will include operational and instrumentation amplifiers for bioelectric event signal conditioning, interfacing and processing; instrumentation noise analysis and filter design; A/D converters and hardware and software principles as related to sampling, storing, processing, and display of biosignals; modeling, analysis, and operation of transducers, sensors, and electrodes, for physiological and imaging systems; and an introduction to ultrasound, X-ray, and optical imaging systems. In addition, students will be involved in three projects of designing and building instrumentation amplifier and filter systems, ultrasound systems, and optical systems. Prerequisites: BME 301A and BME 301B. Same as E62 BME 444 Credit 3 units. EN: TU

E62 BME 550 Numerical Methods for Computational Modeling in Biomedicine
Advanced computational methods are required for the creation of biological models. Students will be introduced to the process of model development from beginning to end, which includes model formulation, how to solve and parameterize equations, and how to evaluate model success. To illustrate the potential of these methods, participants will systematically build a model to simulate a "real-life" biological system that is applicable to their research or interest. A mechanistic appreciation of the methods will be gained by programming the methods in a low-level language (C++) in a Linux environment. While extensive programming knowledge is not required, participants are likely to find that some programming background will be helpful. Students enrolled in the 550 graduate class will be required to complete a final project that incorporates the methods taught in class. Prerequisites: introductory programming course similar to E81 CSE 131. Same as E62 BME 450 Credit 3 units. EN: TU

E62 BME 551 Translational Neuroengineering
This course focuses on the design of bioelectric devices for use in clinical patients. Neural stimulators (e.g., deep brain, vagal) will be the basis for a case-study approach to designing and developing new bioelectrical medical devices. This project-based course will introduce the student to the use of finite element solvers to design novel stimulators. In addition to the engineering design aspects, issues such as product liability, FDA approval, and so on will be discussed. Credit 3 units. EN: TU

E62 BME 5565 Mechanobiology of Cells and Matrices
This course covers several of the fundamental theories of solid mechanics that profoundly affect aspects of human health and disease. This course offers a detailed review of biomechanical inputs that drive cell behavior in physically diverse matrices. In particular, cytoskeletal force-generation machineries, mechanical roles of cell-cell and cell-matrix adhesions, and regulation of matrix deformations are discussed. Also covered are key methods for mechanical measurements and mathematical modeling of cellular response. Implications of matrix-dependent cell motility in cancer metastasis and embryonic development are discussed. Prerequisite: graduate standing or permission of the instructor. Same as E37 MEMS 5565 Credit 3 units. EN: TU

E62 BME 559 Intermediate Biomechanics
This course covers several of the fundamental theories of solid mechanics that are needed to solve problems in biomechanics. The theories of nonlinearity, viscoelasticity and poroelasticity are applied to a large range of biological tissues including bone, articular cartilage, blood vessels, the heart, skeletal muscle, and red blood cells. Other topics include muscle activation, the biomechanics of development and functional adaptation, and the mechanics of hearing. Prerequisites: BME 240 and ESE 318 and ESE 319 or equivalent, or permission of instructor. Credit 3 units. EN: TU
E62 BME 562 Mechanics of Growth and Development
This course applies the fundamental principles of solid mechanics to problems involving growth, remodeling and morphogenesis of cells, tissues and organs. Introduction to developmental biology, nonlinear elasticity, viscoelasticity and active contraction. Particular topics include cellular morphogenetic mechanisms, growth and development of the cardiovascular system, and adaptive remodeling of bone. Prerequisites: BME 240 or MEMS 241 or equivalent. Credit 3 units. EN: TU

E62 BME 564 Orthopaedic Biomechanics — Cartilage/Tendon
Basic and advanced viscoelasticity and finite strain analysis applied to the musculoskeletal system, with a primary focus on soft orthopaedic tissues (cartilage, tendon and ligament). Topics include: mechanical properties of cartilage, tendon and ligament; applied viscoelasticity theory for cartilage, tendon and ligament; cartilage, tendon and ligament biology; tendon and ligament wound healing; osteoarthritis. This class is geared to graduate students and upper-level undergraduates familiar with statics and mechanics of deformable bodies. Prerequisite: BME 240 or equivalent. Note: BME 590Z (BME 463/563) Orthopaedic Biomechanics — Bones and Joints is not a prerequisite. Same as E37 MEMS 5564 Credit 3 units. EN: TU

E62 BME 565 Biosolid Mechanics
Introduction to the mechanical behaviors of biological tissues of musculoskeletal, cardiac and vascular systems. Topics to be covered include static force analysis and nonlinear optimization theory; linearly elastic models for stress-strain analysis and solutions to relevant problems in bioelasticity; models of active structures (e.g., muscles); strain energy methods and nonlinear tissue behaviors; and introductory theory for finite element analysis. Emphasis will be placed on modeling stress-strain relations with relevance to biological tissues. Prerequisites: BME 240 or equivalent and ESE 318 and ESE 319. Same as E62 BME 465 Credit 3 units. EN: TU

E62 BME 569 Cardiac Electrophysiology
This course is an introduction to cardiac electrophysiology with an emphasis on arrhythmia mechanisms, experimental methods, and clinical applications. Topics will include modeling of cardiac rhythms, mapping of cardiac electric activity, pacemakers and defibrillators, and ablation of cardiac tissue. Same as E62 BME 469 Credit 3 units. EN: TU

E62 BME 570 Mathematics of Imaging Science
This course will expose students to a unified treatment of the mathematical properties of images and imaging. This will include an introduction to linear vector space theory, operator theory on Hilbert spaces, and concepts from applied functional analysis. Further, concepts from generalized functions, Fourier analysis, and radon transform will be discussed. These tools will be applied to conduct deterministic analyses of imaging systems that are described as continuous-to-continuous, continuous-to-discrete, and discrete-to-discrete mappings from object properties to image data. In addition, imaging systems will be analyzed in a statistical framework where stochastic models for objects and images will be introduced. Prerequisite: Senior standing or permission of instructor.

E62 BME 572 Biological Neural Computation
This course considers the computations performed by the biological nervous system with a particular focus on neural circuits and population-level encoding/decoding. Topics include Hodgkin-Huxley equations; phase-plane analysis; reduction of Hodgkin-Huxley equations; models of neural circuits; plasticity and learning; and pattern recognition and machine learning algorithms for analyzing neural data. Note: Graduate students in psychology or neuroscience who are in the Cognitive, Computational and Systems Neuroscience curriculum pathway may register in Biol 5657 for 3 credits. For non-BME majors, conceptual understanding, and selection/application of right neural data analysis technique are stressed. Hence homework assignments/exams for the two sections are different, however all students are required to participate in a semester-long independent project as part of the course. Prerequisites: calculus, differential equations, basic probability and linear algebra. Undergraduates need permission of the instructor. Biol 5657 prerequisites: permission from the instructor. Credit 3 units. EN: TU

E62 BME 574 Quantitative Bioelectricity and Cardiac Excitation
Action potential generation, action potential propagation, source-field relationships in homogeneous and inhomogeneous media, models of cardiac excitation and arrhythmia, quantitative electrocardiography. Prerequisites: differential equations, Laplace transform, electromagnetic field theory (undergraduate level). Credit 3 units. EN: TU

E62 BME 575 Molecular Basis of Bioelectrical Excitation
Ion channels are the molecular basis of membrane excitability in all cell types, including neuronal, heart and muscle cells. This course presents the structure and the mechanism of function of ion channels at the molecular level. It introduces the basic principles and methods in the ion channel study as well as the structure-function relation of various types of channels. Exemplary channels that have been best studied are discussed to illustrate the current understanding. Prerequisites: knowledge of differential equations, electrical circuits and chemical kinetics. Credit 3 units. EN: TU

E62 BME 577 Biomedical Product Development
Advances in science and technology have opened the health care field to innovation now more than any other time in history. Engineers and inventors can make real and rapid improvements to patient treatments, length of hospital stay, procedure time, cost containment, and accessibility to treatment. However, a successful transition from idea to implementation requires careful market analysis and strategy planning. This course will address the steps in this process, including personal and team strength assessment, medical need validation, brainstorming initial solutions, market analysis, solution evaluation, regulatory, patent and intellectual property concerns, manufacturability, risk assessment and mitigation, and global considerations. Students will be expected to review resource material prior to coming to class in order to facilitate active class discussion and team-based application of the material during class; regular attendance will be key to course success. The course will focus on applying product development techniques to several real unmet medical needs; students will thus perform analysis and
create reports and presentations for several different product solutions. Peer and faculty evaluations will provide feedback to improve individual technique. In addition, throughout the semester, local biomedical entrepreneurs will visit to share their expertise and experiences. Prerequisites: graduate or professional student standing or permission of the instructor. Credit 3 units.

E62 BME 5772 Biomedical Business Development
For medical innovators, a successful translation from product to market will require careful strategy and an understanding of the steps needed to form and fund a biotech business, either as a new startup or as an extension of the product line of an existing company. This course will address the steps in this process, including intellectual property concerns, R&D, clinical strategy, regulatory issues, quality management, reimbursement, marketing strategy, sales and distribution, operating plans, and approaches to funding. Prerequisites: graduate or professional student standing or permission of the instructor. Credit 3 units.

E62 BME 579 Biofabrication & Medical Devices
This course will cover materials design and modern manufacturing methods for biofabricated tissues and medical devices, with a particular emphasis on bioelectronic devices. Topics will include additive manufacturing and semiconductor photolithography and their materials requirements along with how these methods have evolved to use biomaterials and cells, such as bioprinting. State-of-the-art wearable, in vitro, and implantable devices for diagnostic and therapeutic purposes will be discussed, with emphasis on how their properties have advanced from developments in materials and manufacturing. Lecture materials and assignments will draw heavily from current research and recent scientific literature. All students will be placed on a waitlist. Registration will be split between undergraduate and graduate students. Prerequisite: BME 523 or equivalent biomaterials introductory course preferred. Credit 3 units. EN: TU

E62 BME 5799 Independent Study for Candidates in the Master of Engineering Program
Independent investigation on a topic of special interest. The student and mentor must justify the requested number of units. The MEng program director must approve the requested number of units. Credit variable, maximum 6 units.

E62 BME 5820 Fundamentals and Applications of Modern Optical Imaging
Analysis, design, and application of modern optical imaging systems, with emphasis on biological imaging. The first part of the course will focus on the physical principles underlying the operation of imaging systems and their mathematical models. Topics include ray optics (speed of light, refractive index, laws of reflection and refraction, plane surfaces, mirrors, lenses, aberrations), wave optics (amplitude and intensity, frequency and wavelength, superposition and interference, interferometry), Fourier optics (space-invariant linear systems, Huygens-Fresnel principle, angular spectrum, Fresnel diffraction, Fraunhofer diffraction, frequency analysis of imaging systems), and light-matter interaction (absorption, scattering, dispersion, fluorescence). The second part of the course will compare modern quantitative imaging technologies, including but not limited to digital holography, computational imaging, and super-resolution microscopy. Students will evaluate and critique recent optical imaging literature. Prerequisites: ESE 318 and ESE 319 or their equivalents; ESE 330 or Physics 421 or equivalent. Same as E35 ESE 582
Credit 3 units. EN: TU

E62 BME 589 Biological Imaging Technology
This class develops a fundamental understanding of the physics and mathematical methods that underlie biological imaging and critically examine case studies of seminal biological imaging technology literature. The physics section examines how electromagnetic and acoustic waves interact with tissues and cells, how waves can be used to image the biological structure and function, image formation methods and diffraction limited imaging. The math section examines image decomposition using basis functions (e.g., Fourier transforms), synthesis of measurement data, image analysis for feature extraction, reduction of multidimensional imaging datasets, multivariate regression and statistical image analysis. Original literature on electron, confocal and two photon microscopy, ultrasound, computed tomography, functional and structural magnetic resonance imaging and other emerging imaging technology are critiqued.
Same as E35 ESE 589
Credit 3 units. EN: TU

E62 BME 5901 Integrative Cardiac Electrophysiology
Quantitative electrophysiology of the heart, integrating from the molecular level (ion channels, regulatory pathways, cell signaling) to the cardiac cell (action potential and calcium transient), multicellular tissue (cell-cell communication) and the whole heart. Prerequisite: permission of instructor. Credit 3 units. EN: BME T, TU

E62 BME 5902 Cellular Neurophysiology
This course will examine the biophysical concepts of synaptic function, with a focus on the mechanisms of neural signal processing at synapses and elementary circuits. The course combines lectures and discussion sessions of primary research papers. Topics include synaptic and dendritic structure, electrical properties of axons and dendrites, synaptic transmission, rapid and long-term forms of synaptic plasticity, information analysis by synapses and basic neuronal circuits, principles of information coding, mechanisms of learning and memory, function of synapses in sensory systems, and models of synaptic disease states such as Parkinson's and Alzheimer's diseases. In addition, a set of lectures will be devoted to modern electrophysiological and imaging techniques as well as modeling approaches to study synapses and neural circuits. Prerequisite: senior or graduate standing.
Credit 3 units. EN: BME T, TU

E62 BME 591 Biomedical Optics I: Principles
This course covers the principles of optical photon transport in biological tissue. This course covers the principles and applications of optical photon transport in biological tissue. Topics include a brief introduction to biomedical optics, single-scatterer theories, Monte Carlo modeling of photon transport, convolution for broad-beam responses, radiative transfer equation, diffusion theory and applications, sensing of optical properties and spectroscopy, and photoacoustic imaging principles and applications. Prerequisite: Differential equations. Credit 3 units. EN: TU
E62 BME 5911 Cardiovascular Biophysics Journal Club
This journal club is intended for beginning graduate students, advanced undergraduates and MSTP students with a background in the quantitative sciences (engineering, physics, math, chemistry, etc.). The subjects covered are inherently multidisciplinary. We review landmark and recent publications in quantitative cardiovascular physiology, mathematical modeling of physiologic systems and related topics such as chaos theory and nonlinear dynamics of biological systems. Familiarity with calculus, differential equations and basic engineering/thermodynamic principles is assumed. Knowledge of anatomy/physiology is optional.
Credit 1 unit.

E62 BME 5913 Molecular Systems Biology: Computation & Measurements for Understanding Cell Physiology and Disease
Systems-level measurements of molecules in cells and tissues harbor the promise of identifying the ways in which tissues develop, maintain, age, and become diseased. This class will introduce the systems-level measurement techniques for capturing molecular information and the mathematical and computational methods for harnessing the information from these measurements to improve our understanding of cell physiology and disease. This is a practical class, which involves implementation of the concepts in MATLAB and will be applied to existing, real data from published journal articles. Molecular topics will include gene expression, microRNA, proteins, post-translational modifications, drugs, and splicing. Computational/mathematical topics covered will include statistical inference, dimensionality reduction techniques, unsupervised and supervised machine learning, and graph-based techniques.
Prerequisites: A working knowledge of molecular biology, linear algebra, and statistics is required.
Credit 3 units.

E62 BME 592 Biomedical Optics II: Imaging
This course covers optical imaging technologies. Topics include ballistic imaging, optical coherence tomography, Mueller optical coherence tomography, diffuse optical tomography, photoacoustic tomography, and ultrasound-modulated optical tomography. Prerequisites: Differential equations; Biomedical Optics I: Principles.
Credit 3 units. EN: BME T, TU

E62 BME 594 Ultrasound Imaging
This course will introduce basic principles of ultrasound imaging, diagnostic ultrasound imaging system, clinical applications, and emerging technologies in industry. Prerequisite: ESE 351. Same as E62 BME 494
Credit 3 units. EN: TU

E62 BME 601C Research Rotation for BME Doctoral Students
Credit 3 units.