Biomedical Engineering

About Biomedical Engineering

Biomedical engineering is an interdisciplinary field in which the concepts, methods and techniques of engineering are applied to solving problems in biology and medicine. It applies quantitative, analytical and integrative methods from the molecular level to that of the whole organism to further our understanding of basic biological processes and to develop innovative approaches for the prevention, diagnosis and treatment of disease.

A student majoring in biomedical engineering will have the opportunity to participate in the world-class research activities of engineering and medical faculty in biomaterials, imaging, cardiovascular engineering, cell and tissue engineering, molecular cellular and systems engineering, and neural engineering. All students in biomedical engineering are encouraged to join and be active in the Biomedical Engineering Society (https://www.bmes.org).

Mission Statement

Our departmental mission is to serve society as a center for learning and knowledge creation in engineering and science for the purpose of advancing biology and medicine.

Our overall educational objective is to prepare those receiving a bachelor’s degree in biomedical engineering for a variety of career paths. To that end, our undergraduate curriculum is designed to provide technical proficiency as well as communication and other professional skills so that our graduates will be able to do the following:

• Pursue careers in the biomedical engineering industry or related fields
• Undertake advanced study (e.g., MS, PhD) in biomedical engineering or a related field in preparation for careers utilizing this further training
• Complete professional degrees (e.g., in medicine, dentistry, law or business) in preparation for careers utilizing those degrees

Academic Programs

The Bachelor of Science in Biomedical Engineering (BS–BME) is designed to prepare graduates for the practice of engineering at a professional level. It is accredited by the Engineering Accreditation Commission of ABET (http://www.abet.org).

The curriculum is structured around a basic core of 80 credits. In addition, a complementary set of courses totaling at least 40 credits completes the degree requirements.

In order to satisfy ABET (http://www.abet.org) requirements, all professional engineering curricula at the baccalaureate level must include the equivalent of one and one-half years of engineering topics, including engineering sciences and engineering design appropriate to biomedical engineering. The BS–BME degree at Washington University requires 47 credits of engineering topics. The basic core curriculum includes 32 engineering topics credits. Therefore, students pursuing a BS–BME degree will need 15 additional engineering topics credits beyond the basic core curriculum. They also may receive up to 6 credits of academic credit for a research or design project by registering for BME 400, BME 400A, BME 400B or BME 400C Independent Study. In addition, their course program must include sufficient laboratory experience to ensure competence in experimental design, data collection and data analysis.

For more information regarding engineering topics credit requirements, please refer to the Undergraduate Curriculum (http://bme.wustl.edu/undergraduate/pages/undergraduate-curriculum.aspx) webpage.

Bachelor's/Master's (BS/MS) Program in Engineering

This program allows current BME undergraduate students to earn a master's degree with only one additional year of study. Interested engineering students should discuss the program with their BME academic and Engineering Undergraduate Student Services advisers by the end of their junior year in order to best develop a plan for their senior year leading into their master's year. With adviser and departmental approval, up to 6 graduate-level credits can be shared between the BS and MS degrees; however, the combined program still requires students to complete a minimum of 150 units in total.

Double Majors

An option available to students majoring in biomedical engineering is the double major, which leads to a second professional Bachelor of Science degree in one of the other engineering disciplines in four years. A degree in biomedical engineering combined with a professional degree in one of the traditional engineering disciplines can be expected to enhance employment options in industry. Depending upon the second major chosen, total unit requirements may range from 140 to 148 (or less if the student enters with advanced placement credits). Hence, some summer work may be necessary in order to complete a double major within four academic years. To determine the specific requirements to be satisfied for both degrees, students are urged to consult with an adviser in the second department as early as possible.

Premedical Preparation

Biomedical engineering is also excellent preparation for various professional schools, particularly medical schools. Many students complete their premedical requirements while obtaining
their BME degrees. Premedical preparation is not a major; rather, it allows students to fulfill the requirements needed for entry to medical school. Further information can be obtained by visiting the Premedicine webpage and by contacting the McKelvey School of Engineering’s Health Professions Adviser, Ron Laue, at ron.laue@wustl.edu.

Cooperative Experience

Cooperative experience is available to upper-level students at numerous life science/technology companies both in the St. Louis area and nationwide. This experience is particularly valuable for students who wish to enter industry. However, since most companies ask that students spend the equivalent of one semester and a summer participating in these experiences, it may be difficult to complete the degree requirements in eight semesters, unless students enter with sufficient advanced placement credits and/or take summer courses.

Please visit our website for the most current and up-to-date information.

Phone: 314-935-7208
Website: https://bme.wustl.edu/undergraduate

Faculty

Chair

Lori A. Setton (https://engineering.wustl.edu/Profiles/Pages/Lori-Setton.aspx)
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

Endowed Professors

Rohit V. Pappu (https://engineering.wustl.edu/Profiles/Pages/Rohit-Pappu.aspx)
Edwin H. Murty Professor of Engineering
PhD, Tufts University
Macromolecular self assembly and function; computational biophysics

Yoram Rudy (https://engineering.wustl.edu/Profiles/Pages/Yoram-Rudy.aspx)
Fred Saigh Distinguished Professor of Engineering
PhD, Case Western Reserve University
Cardiac electrophysiology; modeling of the cardiac system

Professors

Jianmin Cui (https://engineering.wustl.edu/Profiles/Pages/Jianmin-Cui.aspx)
PhD, State University of New York–Stony Brook
Ion channels; channel structure-function relationship; biophysics

Daniel Moran (https://engineering.wustl.edu/Profiles/Pages/Daniel-Moran.aspx)
PhD, Arizona State University
Motor control; neural engineering; neuroprosthetics; movement biomechanics

Quing Zhu (https://engineering.wustl.edu/Profiles/Pages/Quing-Zhu.aspx)
PhD, University of Pennsylvania
Biophotonics and multimodality ultrasound and optical imaging

Associate Professors

Dennis L. Barbour (https://engineering.wustl.edu/Profiles/Pages/Dennis-Barbour.aspx)
MD, PhD, Johns Hopkins University
Auditory physiology; sensory cortex neurocircuitry; novel perceptual diagnostics and therapeutics

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

Baranidharan Raman (https://engineering.wustl.edu/Profiles/Pages/Barani-Raman.aspx)
PhD, Texas A&M University
Computational and systems neuroscience; neuromorphic engineering; pattern recognition; sensor-based machine olfaction

Jin-Yu Shao (https://engineering.wustl.edu/Profiles/Pages/Jin-Yu-Shao.aspx)
PhD, Duke University
Cell mechanics; receptor and ligand interactions; molecular biomechanics

Jon Silva (https://engineering.wustl.edu/Profiles/Pages/Jonathan-Silva.aspx)
PhD, Washington University
Ion channel biophysics

Kurt A. Thoroughman (https://engineering.wustl.edu/Profiles/Pages/Kurt-Thoroughman.aspx)
PhD, Johns Hopkins University
Human motor control and motor learning; neural computation
Assistant Professors

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

Nate Huebsch (https://bme.wustl.edu/faculty/Pages/faculty.aspx?bio=114)
PhD, Harvard University
Cell-material Interactions, iPSC-based tissue modeling to study cardiac development and disease

Abhinav Kumar Jha (https://bme.wustl.edu/faculty/Pages/faculty.aspx?bio=125)
PhD, University of Arizona
Development of computational-imaging solutions for diagnosing and treating diseases

Jai S. Rudra (https://engineering.wustl.edu/Profiles/Pages/Jai-Rudra.aspx)
PhD, Louisiana Tech University
Peptide-based biomaterials; immunoengineering; immunology of nanoscale aggregates; development of vaccines and immunotherapies

Michael D. Vahey (https://bme.wustl.edu/faculty/Pages/faculty.aspx?bio=113)
PhD, Massachusetts Institute of Technology
Biophysical mechanisms of infectious disease; fluorescence microscopy; microfluidics

Senior Professor

Larry Taber (https://bme.wustl.edu/faculty/Pages/Larry-Taber.aspx)
PhD, Stanford University
Mechanics of growth and development; cardiac mechanics

Senior Lecturer

Patricia Widder (https://bme.wustl.edu/faculty/Pages/Patricia-Widder.aspx)
MS, Washington University

Lecturer

Noah Ledbetter (https://bme.wustl.edu/faculty/Pages/Noah-Ledbetter.aspx)
PhD, University of Utah

Senior Emeritus Professor

Frank Yin (https://bme.wustl.edu/faculty/Pages/Frank-Yin.aspx)
MD, PhD, University of California, San Diego

Majors

The Major in Biomedical Engineering

The BS in Biomedical Engineering requires completion of the courses in the Core Curriculum as well as five upper-level Tier courses beyond the Core, as described below. Students must meet all McKelvey School of Engineering and Washington University requirements, including the English Composition requirement (please refer to the Engineering Degree Requirements (http://bulletin.wustl.edu/undergrad/engineering/requirements) page). They must also satisfy ABET requirements for a professional degree, which require the accrual of 47 engineering topics units over their course work. A list of Topics Units - Engineering Courses (http://engineering.wustl.edu/current-students/student-services/Pages/default.aspx) is available on the Engineering Student Services website.

The Basic Core

The Biomedical Engineering Core Curriculum consists of 80 credits, outlined below.

<table>
<thead>
<tr>
<th>Courses</th>
<th>Units</th>
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</thead>
<tbody>
<tr>
<td>Physical Sciences</td>
<td></td>
</tr>
<tr>
<td>General Chemistry (Chem 111A, Chem 112A)</td>
<td>6</td>
</tr>
<tr>
<td>General Chemistry Laboratory I, II (Chem 151, Chem 152)</td>
<td>4</td>
</tr>
<tr>
<td>General Physics (Physics 191, 191L, Physics 192, 192L)</td>
<td>18</td>
</tr>
<tr>
<td>Biological Science</td>
<td></td>
</tr>
<tr>
<td>Principles of Biology I (Biol 2960)</td>
<td>4</td>
</tr>
<tr>
<td>Physiological Control Systems (Biol 3058)</td>
<td>2</td>
</tr>
<tr>
<td>Mathematics</td>
<td>6</td>
</tr>
<tr>
<td>Calculus II &amp; III (Math 132, Math 233)</td>
<td>6</td>
</tr>
<tr>
<td>Differential Equations (Math 217)</td>
<td>3</td>
</tr>
<tr>
<td>Engineering Mathematics A &amp; B (ESE 318, ESE 319)</td>
<td>6</td>
</tr>
<tr>
<td>Probability and Statistics for Engineering (ESE 326)</td>
<td>3</td>
</tr>
<tr>
<td>Engineering Science</td>
<td>18</td>
</tr>
<tr>
<td>Computer Science (CSE 131)</td>
<td>3</td>
</tr>
<tr>
<td>Introduction to Electrical and Electronic Circuits (ESE 230)</td>
<td>4</td>
</tr>
<tr>
<td>Biomedical Engineering</td>
<td>7</td>
</tr>
<tr>
<td>Introduction to Biomedical Engineering (BME 140)</td>
<td>3</td>
</tr>
</tbody>
</table>
Students must complete five upper-level Tier engineering courses (15 units), five humanities and social sciences courses (15 units), and three general electives courses (minimum 10 units) beyond the Core Curriculum to complete the major and to prepare for particular fields of employment or education beyond the baccalaureate degree. At least two of the five Tier electives need to be drawn from the Tier I course list below; the remaining three can be chosen from Tier I or Tier II. Students must complete a minimum of 120 units to meet the degree requirements.

### Tier I

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>BME 329</td>
<td>Biothermodynamics in Practice</td>
<td>3</td>
</tr>
<tr>
<td>BME 459</td>
<td>Intermediate Biomechanics</td>
<td>3</td>
</tr>
<tr>
<td>BME 464</td>
<td>Orthopaedic Biomechanics — Cartilage/Tendon (#)</td>
<td>3</td>
</tr>
<tr>
<td>BME 465</td>
<td>Biosolid Mechanics (#)</td>
<td>3</td>
</tr>
<tr>
<td>BME 471</td>
<td>Bioelectric Phenomena</td>
<td>3</td>
</tr>
<tr>
<td>BME 4902</td>
<td>Cellular Neurophysiology</td>
<td>3</td>
</tr>
<tr>
<td>BME 4904</td>
<td>Interfaces and Attachments in Natural and Engineered Structures</td>
<td>3</td>
</tr>
<tr>
<td>BME 494</td>
<td>Ultrasound Imaging</td>
<td>3</td>
</tr>
<tr>
<td>BME 523</td>
<td>Biomaterials Science</td>
<td>3</td>
</tr>
<tr>
<td>BME 5565</td>
<td>Mechanobiology of Cells and Matrices</td>
<td>3</td>
</tr>
<tr>
<td>BME 572</td>
<td>Biological Neural Computation</td>
<td>3</td>
</tr>
<tr>
<td>BME 575</td>
<td>Molecular Basis of Bioelectrical Excitation (#)</td>
<td>3</td>
</tr>
<tr>
<td>BME 5820</td>
<td>Fundamentals and Applications of Modern Optical Imaging</td>
<td>3</td>
</tr>
<tr>
<td>BME 589</td>
<td>Biological Imaging Technology</td>
<td>3</td>
</tr>
<tr>
<td>BME 5902</td>
<td>Cellular Neurophysiology</td>
<td>3</td>
</tr>
</tbody>
</table>

### Tier II

All upper-level (300-500) engineering and physics courses that carry 3 engineering topics units (with the exception of required courses such as BME 301A, BME 301B, BME 320B, and so on) count as Tier II electives.

**Note:** Courses in the Tier I list that are marked with a (#) are offered every other year or less. The most up-to-date Tier lists (https://bme.wustl.edu/undergraduate/pages/undergraduate-curriculum.aspx) can be found on the BME website.

### Minors

A number of undergraduate engineering students pursue a minor in engineering or in another discipline, such as business. For biomedical engineering (BME) majors, there are four engineering minors that are easily obtainable within the typical four-year BME curriculum. These recommended minors require four or fewer additional classes, most of which count toward the electives within the BME major.

**Recommended Engineering Minors for Biomedical Engineering Majors**

- **Bioinformatics:** Bioinformatics is a joint program of the Department of Computer Science & Engineering in the McKelvey School of Engineering and the Department of Biology in the College of Arts & Sciences. Mindful of the emerging opportunities at the interface of biology and computer science, the departments of Biology and of Computer Science & Engineering are sponsoring a bioinformatics minor that will serve students from both departments as well as other students from the natural sciences and engineering with an interest in this field.
- **Computer Science:** Because computing drives innovation in nearly all industries, the Department of Computer Science & Engineering offers a minor in computer science to provide a basic foundation in software and computer science.
- **Electrical Engineering:** This program covers classes in several fields of science and engineering by encompassing electronics, solid-state devices, applied electromagnetics, radiofrequency and microwave technology, fiber-optic communication, applied optics, nanophotonics, sensors, and medical and biological imaging technology.
- **Mechanical Engineering:** The minor in mechanical engineering complements studies in a field related to mechanical engineering, such as biomedical engineering, electrical engineering, physics, chemistry or architecture. The minor is intended to provide students with a credential that could enhance their opportunities for employment or graduate study.

McKelvey School of Engineering offers additional minors; however, they typically require 15 units or more of course work outside the standard BME curriculum. Students who enter with significant transfer credit and/or advanced placement credit may
be able to complete these minors in the standard four years. Otherwise, students will typically require a summer semester or two to complete these minors.

**Engineering Minors Requiring Advanced Placement or Summer Effort for Biomedical Engineering Majors**

- Aerospace Engineering
- Energy Engineering
- Environmental Engineering Science
- Mechatronics
- Nanoscale Science & Engineering
- Robotics
- Systems Science & Engineering
- Physics
- Electronics

**Courses**


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**E62 BME 140 Introduction to Biomedical Engineering**

An introduction to the vast and diverse field of biomedical engineering (BME), this very challenging course has two main purposes. One is to teach students — via lectures, reading assignments, homework and exams — to think on their own, to solve problems, and to know how engineering principles are applied to the areas of bioelectricity, biomechanics, biomolecules, biotechnology and bioimaging. The second is to introduce students — via guest lectures by School of Medicine and engineering faculty — to some of the fascinating and challenging ongoing research in these areas. The course is challenging because students at this early stage, by and large, lack the knowledge base to understand either the engineering/biological aspects of the topical areas or the research being presented. Nevertheless, because future success depends on such, emphasis throughout is placed on developing self-learning as well as quantitative and analytical problem-solving skills, but at an appropriate level. By the end of the course, it is hoped that students will have begun to acquire the skills and approaches necessary to succeed in the engineering curriculum as well as a much more in-depth and informed perspective of BME. Corequisites: Phys 197, Chem 111A, and college-level calculus. Credit 3 units. EN: TU

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**E62 BME 240 Biomechanics**

Principles of static equilibrium and solid mechanics applied to the human anatomy and a variety of biological problems. Statics of rigid bodies with applications to the musculoskeletal system. Mechanics of deformable media (stress, strain; stretching, torsion, and bending) with introduction to nonlinear behavior, viscoelasticity, and growth in living tissue. Applications to cells, bone, muscle, arteries, the heart, and the cochlea. Prerequisite: Phys 197. Credit 3 units. EN: TU

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**E62 BME 240L Biomechanics Laboratory**

This course will consist of hands-on laboratory experiments in topics relevant to bioengineering mechanics such as statics of rigid bodies, viscoelasticity, and stress/strain analysis of biological materials. A focus of the course will be extending fundamental mechanical principles to biological applications through experimentation. The course is designed to follow and enhance the material covered in BME 240. Additionally, students will have the opportunity to design their own experiments, explore topics of special interest, and present their findings. Prerequisites: concurrent or completed BME 240. Credit 1 unit. EN: TU

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**E62 BME 301A Quantitative Physiology I**

A course (lectures, recitation and supervised laboratory sections) designed to elaborate the physiological background necessary for advanced work in biomedical engineering. A quantitative model-oriented approach to physiological systems is stressed. Topics include bioinstrumentation, eye movement, muscle mechanics, action potentials, sensory systems, neuropsychotatics. Prerequisites: BME 140, CSE 131, ESE 230, Biol 3058 (previously Biol 3050 or 3059), ESE 319, or permission of instructor. Credit 4 units. EN: TU

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**E62 BME 301B Quantitative Physiology II**

A course (lecture and supervised laboratory sessions) designed to elaborate the physiological background necessary for advanced work in biomedical engineering. A quantitative model-oriented approach to physiological systems is stressed. Topics include electrocardiography; heart contractility and molecular bases; cell signaling, pulse wave propagation in arteries; pulmonary function; renal function; imaging, and systems biology. Immune system; drug delivery. Prerequisites: BME 140, CSE 131, ESE 230, ESE 319, Biol 3058, or permission of instructor. Credit 4 units. EN: TU

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**E62 BME 320B Biomechanical Therodynamics**

This course covers the foundations of therodynamics with strong emphasis on concepts and the translation of concepts. Topics to be covered include the first and second laws of thermodynamics, probabilistic descriptions of entropy, consequences of the first and second laws in ideal and non-ideal single- and multi-component systems, free energies as descriptors of equilibria in laboratory and biological systems, chemical equilibria, phase equilibria, treatment of aqueous solvents and mixtures, colligative properties, thermodynamics of protein folding, and protein binding equilibria. The material, the lectures, and the homework emphasize learning that enables the translation of concepts into mathematical analysis. A strong background in differential calculus of multiple variables and differential equations (Math 217) is required. Emphasis is placed on regular homework and working in collaborative groups. The main textbook for the course will be "Molecular Driving Forces: Statistical Thermodynamics in Chemistry and Biology," 2nd
E62 BME 329 Biothermodynamics in Practice
This course will include hands-on, laboratory experiments in topics relevant to bioengineering thermodynamics, such as heat transfer, relationships involving temperature and pressure, equilibria, mixing, and solution chemistry. A focus of the course will be extending fundamental scientific principles to biological applications. Students will have the opportunity to design their own experiments, explore topics of special interest, and present their findings. Prerequisites: Chem 111A and 151; Physics 117A, 118A or 197, 198.
Credit 3 units. EN: TU

E62 BME 366 Transport Phenomena in Biomedical Engineering
Many processes of importance in biology and medicine involve the transfer of mass, heat, or momentum. Through the use of the differential control volume approach, the fundamental transport equations will be derived. Systematic derivation of differential equations appropriate for different types of transport problems will be explored. Solutions of the resulting differential equations for simple chemical/biological systems will then be sought. Macroscopic descriptions of fluid flow will be applied to the design of blood pumps for the heart. Unsteady mass transfer with diffusion, advection and chemical reactions will also be applied to the transport of proteins, metabolites and therapeutics throughout the body. Prerequisites: BME 240, Math 217, ESE 318 and ESE 319, BME 320B.
Credit 3 units. EN: TU

E62 BME 400 Independent Study
Independent investigation on topic of special interest. This course has no engineering topics units. Prerequisites: junior or senior standing and approval of the BME Undergraduate Studies Committee.
Credit variable, maximum 6 units.

E62 BME 400A Independent Study
Independent investigation on a topic of special interest. This course has 1 unit of engineering topics. The student and mentor must justify the number of engineering topic units being requested, and the BME Undergraduate Studies Committee must approve the requested number of engineering topics. Prerequisites: junior or senior standing and approval of the BME Undergraduate Studies Committee.
Credit 1 unit. EN: TU

E62 BME 400B Independent Study
Independent investigation on a topic of special interest. This course has 2 units of engineering topics. The student and mentor must justify the number of engineering topic units being requested, and the BME Undergraduate Studies Committee must approve the requested number of engineering topics. Prerequisites: junior or senior standing and approval of the BME Undergraduate Studies Committee.
Credit 2 units. EN: TU

E62 BME 400C Independent Study
Independent investigation on a topic of special interest. This course has 3 units of engineering topics. The student and mentor must justify the number of engineering topic units being requested, and the BME Undergraduate Studies Committee must approve the requested number of engineering topics. Prerequisites: junior or senior standing and approval of the BME Undergraduate Studies Committee.
Credit 3 units. EN: TU

E62 BME 401A Senior Capstone Design A
A hands-on design experience to provide students practical application of engineering. Working in small teams, students will either meet with possible clients to design a prototype or bring an original idea of their own to the class. The students will work on an original design or redesign of a component or system of biomedical engineering significance. The students will be taught how to craft a project scope with the required design specifications. The design experience will require application of knowledge and skills acquired in earlier course work; it will incorporate engineering standards and realistic constraints that include most of the following considerations: economic, environmental, sustainability, manufacturability, ethical, health and safety, FDA, social and political. Students will prepare written reports and present their designs orally to a panel of faculty members and industrial representatives. The final product of BME 401A will be a descriptive paper design of their solution. Prerequisite: BME senior standing.
Credit 2 units. EN: TU

E62 BME 401B Senior Capstone Design B
A hands-on design experience to provide students practical application of engineering. Working in small teams, students will work toward building a prototype of the student design which was a product of 401A. The students will be expected to design a verification and validation plan to test the prototype built. The design experience will require application of knowledge and skills acquired in earlier course work and lab experiences; it will incorporate engineering standards and realistic constraints that include most of the following considerations: economic, environmental, sustainability, manufacturability, ethical, health and safety, FDA, social and political. Students will prepare written reports and present their designs orally to a panel of faculty members and industrial representatives. The final product of BME 401B will be a prototype, and a descriptive paper describing their solution documenting how the prototype satisfies the design specifications, with the validation and verification results. Prerequisites: BME 401A.
Credit 2 units. EN: TU

E62 BME 410 International Community Service Learning Project
This pass/fail course is a two-week summer international experience in conjunction with the faculty and students of our partner, The Biomedical Engineering Institute of Hong Kong Polytechnic University. Students first attend an orientation at HKPU to learn about functional electrical stimulation (FES) and treating cerebral palsy with orthotic devices. The entire group then goes to a clinic in mainland China where they put into practice what they have learned, the former in patients who have suffered strokes and the latter in children with cerebral palsy — working in teams to diagnose, fit and fabricate orthotic devices. A written summary of the experience is the final product. Academic credits are awarded at the end of the fall semester following the
E62 BME 432 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. Credit 3 units. EN: TU

E62 BME 442 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 lecture, 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. Prerequisites: basic knowledge of genes and cloning. Credit 3 units. EN: TU

E62 BME 443 Molecular and Cellular Engineering
The ability to engineer biological function at the cellular level holds tremendous potential for both basic and applied science. This course aims to provide knowledge and practical proficiency in the methods available for measuring and controlling the molecular organization of eukaryotic cells. Topics to be covered include genome engineering using viral- and CRISPR-Cas systems; spatial and temporal control of proteins and their interactions; methods for characterizing and engineering posttranslational modications; and the relationship between cellular organization and function in migration, immune cell target recognition, and differentiation. Examples from recent scientific literature will provide the foundation for these topics. Credit 3 units. EN: TU

E62 BME 444 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. Credit 3 units. EN: TU

E62 BME 450 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. Credit 3 units. EN: TU

E62 BME 459 Intermediate Biomechanics
This course covers several of the fundamental theories of solid mechanics that are needed to solve problems in biomechanics. The theories of nonlinear elasticity, 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 function, adaptation, and the mechanics of hearing. Prerequisites: BME 240 and ESE 318 and ESE 319 or equivalent, or permission of instructor. Same as E62 BME 559 Credit 3 units. EN: TU

E62 BME 464 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. Prerequisites: 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 465 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. Credit 3 units. EN: TU

E62 BME 470 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. Concepts from generalized functions, Fourier analysis, and Radon transform will also 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 in which stochastic models for objects and images will be introduced. Prerequisite: senior standing or instructor permission. Same as E62 BME 570 Credit 3 units.

E62 BME 471 Bioelectric Phenomena
This course is a quantitative introduction to the origins of bioelectricity with an emphasis on neural and cardiac electrophysiology. Topics include electric fields and current flow in volume conductors; cell membrane channels and their role in generating membrane potentials; action potentials and their propagation in myelinated and unmyelinated axons as well as cardiac tissue. Minor topics of discussion include both skeletal muscle and nonhuman (e.g., electric fish) sources of bioelectricity. Prerequisite: ESE 330. Credit 3 units. EN: TU

E62 BME 472 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/examinations 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. Same as E62 BME 572 Credit 3 units. EN: TU

E62 BME 4902 Cellular Neurophysiology
This course will examine the biophysical concepts of synaptic function, with 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 and will be placed on modeling stress-strain relations with relevance to biological tissues. Prerequisites: BME 240 or equivalent and ESE 318 and ESE 319. Credit 3 units. EN: TU

E62 BME 494 Ultrasound Imaging
Introduction to basic principles of ultrasound imaging, diagnostic ultrasound imaging systems, clinical applications, and emerging technologies in industry. Prerequisite: ESE 351. Credit 3 units. EN: BME T, TU

E62 BME 501C BME Doctoral Seminar Series
This is a 1-unit 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 you attended. Papers are to be submitted to the graduate student administrator for review by the director of doctoral studies. Prerequisites: Students must be current BME students in their second year or beyond in order to register. 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 5074 Biomedical Devices
Understanding of how medical devices are designed, tested, and used in clinical settings. Topics include design, manufacturing, and regulatory considerations for medical devices. Prerequisites: BME 366 or equivalent and MEMS 3410, Biol 2960 and 2970; or permission of the instructor. Credit 3 units.

E62 BME 5075 Translational Regenerative Medicine
This course is designed for upper-level undergraduates and first-year graduate students with a background in engineering. This course 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. The course will include two lectures per week and one discussion section. In the discussion section, the emphasis will be on experimental techniques used in cell biology and the critical analysis for primary literature. Note that this course does not count for engineering topics credits and 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 4 units.

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.

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.

E62 BME 530A Molecular Cell Biology for Engineers
This class is designed to provide upper-level undergraduates and first-year graduate students with a background in engineering. This class 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. The course will include two lectures per week and one discussion section. In the discussion section, the emphasis will be on experimental techniques used in cell biology and the critical analysis for primary literature. Note that this course does not count for engineering topics credits and 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 4 units.

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 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/chotic/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 the discovery of gene regulatory networks, the quantitative modeling of gene regulatory networks, synthetic biology, and (in some years) the quantitative modeling of metabolism. Prerequisite: CSE 131 or CSE 501N.
Same as E81 CSE 587A
Credit 3 units. EN: 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, receptor tyrosine kinases, adhesion signaling, the MAPK cascade, lipid signaling, the DNA damage response, and autocrine, paracrine and juxtacrine signaling. Prerequisites: BME 530A or BME 506B.
Credit 3 units.

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 lecture, 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. Prerequisites: basic knowledge of genes and cloning.
Same as E62 BME 442
Credit 3 units. EN: TU

E62 BME 543 Molecular and Cellular Engineering
The ability to engineer biological function at the cellular level holds tremendous potential for both basic and applied science. This course aims to provide knowledge and practical proficiency in the methods available for measuring and controlling the molecular organization of eukaryotic cells. Topics to be covered include genome engineering using viral- and CRISPR-Cas systems; spatial and temporal control of proteins and their interactions; methods for characterizing and engineering post-translational modifications; and the relationship between cellular organization and function in migration, immune cell target recognition, and differentiation. Examples from recent scientific literature will provide the foundation for these topics.
Same as E62 BME 443
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.

E62 BME 565 Mechanobiology of Cells and Matrices

At the interface of the cell and the extracellular matrix, mechanical forces regulate key cellular and molecular events 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: BME T, 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 nonlinear elasticity, 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 or ESE 319 or equivalent, or permission of instructor. Same as E62 BME 5565.

Credit 3 units. EN: BME T, 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: BME T, 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 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 instructor permission.

Credit 3 units.

E62 BME 5702 Application of Advanced Engineering Skills for Biomedical Innovators

Students will work in small teams to apply core engineering skills covered in BME 5701 such as FEM, CAD, microcontroller programming, circuit design, data informatics, and app development to particular clinical needs or processes chosen by the instructing staff. Prerequisites: BME 5701 or permission of instructor.

Credit 3 units.

E62 BME 5711 Ideation of Biomedical Problems and Solutions

This course is part one of the year-long master's design sequence for the BME Master of Engineering. The course will begin with a boot camp primer of HIPAA certification, clinical etiquette, medical law, and intellectual property law. This will be followed by a rotation period of guided shadowing of clinicians. Following each rotation, students will review and present their findings, with a view toward problem solving and project generation. Three-fourths of the way through the course, students will form into teams, choose a master's project, and begin intensive study of their chosen problem or process. The final weeks of the course will focus on problem scope and definition, identification of creative alternatives, and consultation with experts in the field. Prerequisite: acceptance into the Master of Engineering program.

Credit 3 units.
E62 BME 5712 Implementation of Biomedical Solutions
This course is part two of the year-long master's design sequence for the BME Master of Engineering. Students will work in small groups to begin to design a solution to the problem identified in BME 5711. Options and alternatives will be evaluated and a best-choice solution will be chosen, based on an in-depth study of constraints upon the problem, including engineering materials, economic, safety, social, manufacturing, ethical, sustainability, and other requirements. Core skills such as FEM, CAD, circuit design, microcontroller programming, and 3-D printing will be applied to create first an alpha mockup for proof of concept, followed by a full working prototype by the end of the semester. Prerequisites: BME 5711 or permission of instructor. Credit 3 units.

E62 BME 5713 Translation of Biomedical Solutions to Products
This course is the third and final part of the year-long master's design course sequence. Through a repeated sequence of iteration, fabrication and verification, design teams will refine and optimize their master's design project, bringing it to completion. Prerequisites: BME 5712 or permission of instructor. Credit 4 units.

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 to model 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/examinations 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 5722 Feasibility Evaluation of Biomedical Products
This is the second course of the Master of Engineering - Biomedical Innovation sequence in product development. Students will practice the steps in biomedical product development, including medical need validation, brainstorming initial solutions, market analysis, solution evaluation, regulatory, patent, and intellectual property concerns, manufacturability, risk assessment and mitigation, and global considerations. 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. Local biomedical entrepreneurs will also visit to share their expertise and experiences. Prerequisite: admission to the Master of Engineering program. Credit 2 units.

E62 BME 5723 Realization of Biomedical Products in the Marketplace
This course is the third in the MEng-BMI Biomedical Product Development sequence, focusing on the final stages of analysis to bring forth a leading solution concept. Solution concepts are screened for killer risks in the areas of intellectual property, regulatory, reimbursement, business models, and technical feasibility to identify viable concepts. From there, manufacturability and product specifications are evaluated against user and design requirements to select a concept that offers the highest value with lowest risk. Throughout the course, students will practice effective communication of risk factors through pitch presentations and executive summary reports. In addition, specialists from the St. Louis entrepreneurial community will share their experiences as guest speakers. Prerequisites: BME 5722; MEng-BMI candidates only. Credit 1 unit.

E62 BME 5731 Business Foundations for Biomedical Innovators
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 provide a first look at 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: MEng program. Credit 2 units.

E62 BME 5732 Entrepreneurship for Biomedical Innovators
This course will apply the concepts covered in BME 5731 in an interactive process that will provide practical experience. Topics of intellectual property, R&D, clinical strategy, regulatory issues, quality management, reimbursement, marketing strategy, sales and distribution, operating plans, and approaches to funding will be covered. Along with practical exercises, access to specialists and experts in these topics from the St. Louis entrepreneurial community will be provided as an integral part of the course. Prerequisites: BME 5731; MEng-BMI candidates only. Credit 2 units.

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 Bioelectric 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.
Optical Imaging

E62 BME 5771 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 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: BME T, 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: BME T, 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. 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 and diffusion theory, hybrid Monte Carlo method and diffusion theory, and sensing of optical properties and spectroscopy. 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. EN: 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