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.
Credit 3 units. EN: TU

E62 BME 220 Introduction to Biomedical Circuits
Electricity is central to normal and abnormal biological function, spanning scales from the subcellular to whole systems. Scientists and engineers also use electrical engineering to design and implement interaction with biological tissue, from classical physiological experiments to cutting-edge brain-computer interfaces. This course will begin the study of bioelectrical engineering by introducing simple electrical elements, circuits, amplifiers, and instrumentation. Relevant biological examples and computer modeling will be used throughout. The lab component will provide hands-on laboratory practice with simple electrical elements, circuits, amplifiers, instrumentation, and computer modeling, with a focus on biomedical applications. BME 220 fulfills the circuits requirement for BME students in place of ESE 230.
Prerequisite: L31 Phys 192/192L; Corequisite: Math 217.
Credit 4 units. EN: TU

E62 BME 220L Biomedical Circuits Laboratory
This course covers the lab portion only of E62 BME220. It is open only to those students who have completed an approved lecture-only circuits course and who need to fulfill the circuits lab requirement for the BS-BME degree. Students wishing to enroll will be placed on a waitlist and reviewed by the BME department.
Credit 1 unit. EN: TU

E62 BME 231 Foundations of Biomedical Computing
This elective course provides a basis for solving problems in biomedical engineering through coding and computation. Coding structures applied to concepts in linear algebra, statistics, and probability are introduced as a foundation to more advanced biomedical data science applications in machine learning and artificial intelligence. The course is taught using Python; no prior knowledge of Python is expected or required. Students should be comfortable with high school level algebra and geometry. This course is required as prerequisite for BME440, Biomedical Data Science, and is a required course for the Biomedical Data Science minor.
Credit 3 units. EN: TU

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: L31 Phys 191 or L31 Phys 193.
Credit 3 units. EN: TU

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. Prerequisite or Corequisite: E62 BME 140.
Credit 1 unit. EN: TU

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, neuroprosthetics. 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

E62 BME 301B Quantitative Physiology II
This course covers the foundation of thermodynamics 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,
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, equilibrium, 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: L07 Chem 11A, L07 Chem 151, L31 Phys 191/191L, and L31 Phys 192/192L. 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: E62 BME 240, L24 Math 217, E35 ESE 318, and E55 ESE 319. Credit 3 units. EN: TU

E62 BME 400 Independent Study
Independent investigation on a 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: BME T, 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 discern a biomedical problem, or bring an original idea of their own to the class. The students will work on an original design or redesign of an existing solution to address the unmet need. The design experience will involve application of knowledge and skills acquired in earlier coursework. It will also incorporate best practices in biomedical data science, including ethical considerations such as respect for persons, social license, and vulnerabilities, patient safety and privacy, and HIPAA compliance. Students will be guided through the design process and will produce and present appropriate deliverables for their project. This course is required for the Biomedical Data Science minor. Prerequisites: BME 440 or consent of instructor. Credit 3 units.

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 coursework 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 descriptive paper design of their solution. Prerequisite: BME senior standing. Credit 2 units. EN: TU

E62 BME 401C Senior Capstone Design C
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 coursework 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
ESE 318, E35 ESE 326, (E62 BME 231 or E81 CSE 217A), or equivalent
implement an independent project to address a biomedical data
communicate information about datasets, and they will design and
will learn to prepare, transform, visualize, validate, model, and
biomedical data science topics from their research areas. Students
prepare written reports and participate in oral
design reviews involving a panel of faculty members and industrial
representatives. Prototype construction is the final goal of the class.
Prerequisites: BME 401, senior standing, and approval of the instructor.
Credit 1 unit. 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
summer experience. Prerequisites: completion of junior year, BME 301A.
Enrollment: Students must apply by Feb. 1 each spring. Enrollment is
restricted to 10 of the applicants.
Credit 2 units.

E62 BME 432 Physics of Biopolymers
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 440 Biomedical Data Science
This course will cover data analysis, statistical methods, AI, machine
learning, predictive modeling, and data visualization, with applications
to medicine and health. As part of the course, BME faculty will present
biomedical data science topics from their research areas. Students
will learn to prepare, transform, visualize, validate, model, and
communicate information about datasets, and they will design and
implement an independent project to address a biomedical data
science problem. Prior Python experience required. Prerequisites: E35 ESE 318, E35 ESE 326, (E62 BME 231 or E81 CSE 217A), or equivalent
courses.
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
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.
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 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.
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. Prerequisite: E61 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 functional 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 462 Human-Machine Interfaces
This course will provide an overview of neurorehabilitation technologies for individuals with neuromotor disorders. Topics will include the neurophysiology of human motor and sensory systems, motor control and adaptation, and neuromotor plasticity in the damaged brain and spinal cord. Human-machine interface systems including prostheses, orthoses and exoskeletons, wheelchairs, neuroprosthetics, brain-machine interfaces, and wearable robots will be discussed with an emphasis on their clinical applications for restoration of motor and sensory functions. Lecture material and assignments will draw from current scientific literature and research. All students will be placed on a waitlist. Registration will be split between undergraduate and graduate students. Prerequisite: BME 301 Quantitative Physiology I or equivalent introductory physiology course preferred.
Credit 3 units.
EN: BME T, 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 469 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 arrhythmias, mapping of cardiac electric activity, pacemakers and defibrillators, and ablation of cardiac tissue.
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. 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. Familiarity with engineering-level mathematics, calculus, linear algebra, and introduction to Fourier analysis is expected. Prerequisite: Senior standing or permission of instructor.
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 will include electric fields and current flow in volume conductors; cell membrane channels and their role in generating membrane potentials; and action potentials and their propagation in myelinated and unmyelinated axons as well as cardiac tissue. Minor topics of discussion will include both skeletal muscle and non-human (e.g., electric fish) sources of bioelectricity.
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 4735 Biomedical Engineering Entrepreneurship
Students will learn about entrepreneurship, including IP, business development, and fundraising, through case studies. Credit 3 units.

E62 BME 4739 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 their materials requirements along with how these methods have evolved to use biomaterials and cells, such as bioprinting. State-of-the-art 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 material and assignments will draw from both current market devices and the clinical standard-of-care as well.
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 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. Same as E62 BME 5902 Credit 3 units. EN: TU

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. E37 MEMS 3610 OR MEMS 3601 OR permission of instructor.

CREDIT 3 UNITS. EN: TU

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 processes occurring in 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 in Engineering or DBBS.

CREDIT 3 UNITS.

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
This course is designed for graduate students with little or no background in biomedical signal processing, with an emphasis on time- and frequency-domain analyses of biomedical signals and their applications to a variety of real-world biomedical problems. Technical topics of this course include a review of linear signals and systems theory, biomedical system modeling, time-domain analysis, frequency transforms, frequency-domain analysis, linear filter design, signal truncation and sampling, discrete Fourier transform, and fast Fourier transform. Application topics include noise analysis of biomedical signals and frequency analysis and machine learning in biomedical image processing. Concepts learned in class will be applied using software tools to biomedical signals such as biological rhythms, EMG, ECG, EEG, and biomedical images. 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), sequence alignment, and identification of transcription-factor binding sites. Systems biology
topics include the mapping of gene regulatory networks, quantitative modeling of gene regulatory networks, synthetic biology, and applications of deep learning in computational biology. Prerequisite: CSE 131 or CSE 501N.
Same as E81 CSE 587A
Credit 3 units. EN: BME T, TU

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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 close-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. Prerequisite: BME 530A or BME 5068.
Credit 3 units.

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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/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

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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

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E62 BME 540 Systems Analysis of Biological Signaling
This course covers biochemical and computational methods of cellular signaling pathway analysis. Topics include kinetics, differential equations, and sensitivity analysis, with emphasis on cellular and molecular vascular signaling in health and disease. Prerequisites: Biol 2060 and Math 217
Credit 3 units. EN: TU

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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

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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: E81 131.
Same as E62 BME 450
Credit 3 units. EN: TU

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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. Prerequisite: BME 471
Credit 3 units. EN: TU

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E62 BME 5565 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: TU

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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 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 5642 Human-Machine Interfaces
This course will provide an overview of neurorehabilitation technologies for individuals with neuromotor disorders. Topics will include the neurophysiology of human motor and sensory systems, motor control and adaptation, and neuromuscular function. The damaged brain and spinal cord. Human-machine interface systems including prostheses, orthoses and exoskeletons, wheelchairs, neuroprosthetics, brain-machine interfaces, and wearable robots will be discussed with an emphasis on their clinical applications for restoration of motor and sensory functions. Lecture material and assignments will draw from current scientific literature and research. All students will be placed on a waitlist. Registration will be split between undergraduate and graduate students. Prerequisite: BME 301 Quantitative Physiology I or equivalent Introductory physiology course preferred. Same as E62 BME 4642 Credit 3 units. EN: BME T, 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 bielasticity; 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 arrhythmias, 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. Familiarity with Engineering-level mathematics, Calculus, Linear algebra, introduction to Fourier analysis is expected. Prerequisite: Senior standing or permission of instructor. Credit 3 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; 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. Undergraduate need permission of the instructor. Biol 5657 prerequisites: permission from the instructor. Credit 3 units. EN: TU

E62 BME 5735 Biomedical Engineering Entrepreneurship
Students will learn about entrepreneurship, including IP, business development, and fundraising, through case studies. Same as E62 BME 4735 Credit 3 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 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 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 5791 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 5792 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 their materials requirements along with how these methods have evolved to use biomaterials and cells, such as bioprinting. State-of-the-art 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 material and assignments will draw from both current market devices and the clinical standard-of-care as well as ongoing research and recent scientific literature. All students will be placed on a waitlist. Registration will be split between undergraduate and graduate students. Prerequisite: E62 BME 523 or equivalent biomaterials introductory course

Same as E62 BME 479

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 E5 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 E5 ESE 589

Credit 3 units. EN: TU

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 E5 ESE 582

Credit 3 units. EN: TU

E62 BME 589 Biological Imaging Technology

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Same as E5 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: 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: Familiarity with differential equations and partial 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 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: L24 Math 217; E62 BME 591. Credit 3 units. EN: BME T, TU

E62 BME 594 Ultrasound Imaging
Ultrasound imaging is the most widely used medical imaging modality in the world. This course offers an introduction to the medical ultrasound field. It exposes students to fundamental physical principles of ultrasound, ultrasound imaging, and ultrasound therapy. It will also introduce emerging ultrasound technologies in industry and clinics. Students will learn via lectures, homework, lab exercises, and a final project to gain knowledge, learn the ability to think critically, and develop problem-solving skills. Same as E62 BME 494. Credit 3 units. EN: TU

E62 BME 595 Drug Delivery Systems: Principles and Applications
Drug delivery is a promising approach for transporting pharmaceutical treatments in the body to safely achieve the desired therapeutic effect, while reducing the undesired side effects. This course will introduce students to the fundamental concepts of drug pharmacokinetics and dynamics, the biological and physicochemical principles drug delivery systems are based on, and the advantages of such delivery systems. Additionally, we will introduce the design and development of advanced drug delivery platforms such as nano-carriers, cell/gene delivery systems, drug-polymer conjugates and their relevant clinical applications. Finally, we will be having guest speakers from the industry, the university, as well as the office of technology management for Interdisciplinary Innovation & Entrepreneurship. Credit 3 units.