BIOMEDICAL ENGINEERING

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Engineering methods and strategies are used to address biomedical problems ranging from studies of physiological function using images to the development of artificial organs and new biomaterials. The B.S. degree in Biomedical Engineering is designed to provide students with an understanding of common fundamental methodologies and the ability to develop quantitative approaches to one of four biomedical engineering tracks: Bioimaging, Biomechanics and Mechanobiology, Biomolecular Engineering, and Systems Biology. The flexible course structure of the major permits students to bridge basic concepts in the life sciences and traditional areas of engineering, while also gaining a comprehensive understanding of biomedical engineering as a field of study.

PREREQUISITES

The following prerequisites are common to all tracks in the major: BIOL 101 and 102 (or a higher-level course in MCDB or MB&B, with permission of the director of undergraduate studies); a lecture course in chemistry numbered CHEM 161 or higher; ENAS 194; MATH 115; MATH 120 or ENAS 151; PHYS 180, 181, 205L, and 206L (or 165L and 166L, with DUS permission).

REQUIREMENTS OF THE MAJOR

The major for the Class of 2019 With DUS approval, the following changes to the requirements of the major may be fulfilled by students who declared their major under previous requirements.

The major for the Class of 2020 and subsequent classes Students must complete twelve term courses, totaling at least eleven course credits, beyond the prerequisites, including at least three required courses in the chosen track; two terms of a biomedical engineering laboratory (BENG 355L, 356L); BENG 280, a half-credit course taken sophomore year as part of the senior requirement; and the senior requirement (see below). During the first year, students study basic mathematics, chemistry, and biology. By the end of the sophomore year, they have taken physics, ENAS 194, BENG 249, and BENG 350. In the junior year, students gain a comprehensive grounding in the field through BENG 351, BENG 352, BENG 353, BENG 355L, and BENG 356L. During the junior and senior years students also acquire depth by taking electives in one of the four areas of concentration. A senior seminar and a senior project give students practical, detailed information about their chosen area of concentration. By the end of senior year, two term courses in the life sciences must have been included among the prerequisite and required courses for the major. One relevant course (e.g., MB&B 300) may be substituted with the permission of the DUS.

Students in all tracks are required to take the following seven term courses: BENG 249, 280, 350, 351, 352, 353, 355L, and 356L.

Students in the *Bioimaging track* must also take three courses chosen from BENG 404, 406, 410, 444, 445, 475, 476, or 485.

Students in the *Biomechanics and Mechanobiology track* must also take three courses chosen from MENG 185, 280, 361, BENG 404, 410, 434, 453, 455, 456, 457, or 458.

Students in the *Biomolecular Engineering track* must also take three courses chosen from BENG 404, BENG 410, 411, 434, 435, 463, 464, 465, 467, or MENG 361.

Students in the *Systems Biology track* must also take three courses chosen from BENG 404, 410, 411, 434, 435, 463, 464, 465, 467, or MENG 361.

Research Courses Students are permitted, and encouraged, to engage in research before the senior year by enrolling in BENG 471 and/or BENG 472. These courses, offered Pass/Fail, may be taken more than once for credit, but repeated courses do not count toward the major. See Course Credits and Course Loads in the Academic Regulations.

Credit/D/Fail No course taken Credit/D/Fail may count toward the major, including prerequisites.

Roadmap See visual roadmap of the requirements.

SENIOR REQUIREMENT

In their senior year, all students must enroll in BENG 480 (for the Class of 2020 and beyond, this is a half-credit course). They must also complete a one-term senior project in their final term of enrollment (BENG 474) or a two-term, yearlong project (BENG 473, 474).

ADVISING

Preparation for graduate study The Biomedical Engineering curriculum is excellent preparation for graduate study in engineering, science, and medicine. In some cases, organic chemistry and/or certain biology courses may be substituted for one course in the major after consultation with the director of undergraduate studies.

REQUIREMENTS OF THE MAJOR

Prerequisites BIOL 101 and 102, or higher-level course in MCDB or MB&B with DUS permission; 1 lecture course in chemistry numbered CHEM 161 or higher; ENAS 194; MATH 115; MATH 120 or ENAS 151; PHYS 180, 181, and 205L, 206L (or 165L, 166L with DUS permission)

Number of courses 12 term courses, totaling at least 11 course credits, beyond prereqs (incl senior req)

Specific courses required *All tracks*—BENG 249, 280, 350, 351, 352, 353, 355L, 356L; *Bioimaging track*—3 from BENG 404, 406, 410, 404, 445, 475, 476, 485; *Biomechanics and Mechanobiology track*—3 from MENG 185, 280, 361, BENG 404, 410, 434, 453, 455, 456, 457, 458; *Biomolecular Engineering track*—3 from BENG 404, 410, 411, 434, 435, 463, 464, 465, 467, MENG 361; *Systems Biology track*—3 from BENG 404, 410, 411, 434, 435, 463, 464, 465, 467, MENG 361

Distribution of courses 2 term courses in life sciences among prereq and req courses

Substitution permitted Relevant course with DUS permission

Senior requirement BENG 480 and a one-term senior project in final term of enrollment (BENG 474), or yearlong senior project (BENG 473 and 474)

FACULTY OF THE DEPARTMENT OF BIOMEDICAL ENGINEERING

Professors Richard Carson, †Nicholas Christakis, James Duncan, Jay Humphrey, Fahmeed Hyder, Andre Levchenko, †Laura Niklason, Douglas Rothman, Mark Saltzman, †Martin Schwartz, †Frederick Sigworth, †Brian Smith, Lawrence Staib, †Hemant Tagare, †Paul Van Tassel, Steven Zucker, †Robin de Graaf, Themis Kyriakides, †Evan Morris, †Xenophon Papademetris,

Associate Professors Tarek Fahmy, †Corey Wilson, †Joerg Bewersdorf, Stuart Campbell, †Michael Choma, Rong Fan, Anjelica Gonzalez, †Chi Liu,

Assistant Professors Michael Mak, Kathryn Miller-Jensen, Michael Murrell, †Steven Tommasini, †Jiangbing Zhou

Lecturers †Liqiong Gui, †Jing Zhou

†A joint appointment with primary affiliation in another department or school.

Courses

*** BENG 205a, Discovery and Design in Biomedical Research** Jay Humphrey
Multi-disciplinary and team-based research approach to the study of clinical dilemma. Focus on an important health care problem, bringing to bear concepts and principles from diverse areas to identify possible solutions. Study of precision regenerative medicine as it involves aspects of bioengineering, materials science, immunobiology, mechanobiology, computational modeling, and experimental design, as well as hands-on fabrication and materials testing (i.e., data collection and analysis). Prerequisites: MATH 115 and MATH 120 or ENAS 151. SC

BENG 249b, Introduction to Biomedical Computation Michael Mak
Computational and mathematical tools used in biomedical engineering for the simulation of biological systems and the analysis of biomedical data. Basics of computational programming in MATLAB; applications to modeling, design, and statistical and data analysis. Prerequisite: MATH 120 or ENAS 151. QR

*** BENG 280a, Sophomore Seminar in Biomedical Engineering** Kathryn Miller-Jensen
Study of past successes and future needs of the multidisciplinary field of biomedical engineering. Areas of focus include: biomolecular engineering, including drug delivery and regenerative medicine; biomechanics, including mechanobiology and multiscale modeling; biomedical imaging and sensing, including image construction and analysis; and systems biology. ½ Course cr

*** BENG 350a / MCDB 310a, Physiological Systems** Mark Saltzman and Stuart Campbell
Regulation and control in biological systems, emphasizing human physiology and principles of feedback. Biomechanical properties of tissues emphasizing the structural basis of physiological control. Conversion of chemical energy into work in light of metabolic control and temperature regulation. Prerequisites: CHEM 165 or 167 (or CHEM 113 or 115), or PHYS 180 and 181; MCDB 120, or BIOL 101 and 102. SC

BENG 351b / CENG 351b, Biotransport and Kinetics Kathryn Miller-Jensen
Creation and critical analysis of models of biological transport and reaction processes. Topics include mass and heat transport, biochemical interactions and reactions, and thermodynamics. Examples from diverse applications, including drug delivery, biomedical imaging, and tissue engineering. Prerequisites: MATH 115, ENAS 194; BIOL 101 and 102; CHEM 161, 163, or 167; BENG 249. QR

BENG 352b, Biomedical Signals and Images James Duncan and Lawrence Staib
Principles and methods used to represent, model, and process signals and images arising from biomedical sources. Topics include continuous and discrete linear systems analysis, Fourier analysis and frequency response, metrics for signal similarity, and noise filtering. Biomedical examples range from one-dimensional electrical signals in nerves and muscles to two-dimensional images of organs and cells. Prerequisite: MATH 120 or ENAS 151. BENG 249, 350, and ENAS 194 strongly recommended. QR

BENG 353a / PHYS 353a, Introduction to Biomechanics Michael Murrell
An introduction to the biomechanics used in biosolid mechanics, biofluid mechanics, biothermomechanics, and biochemomechanics. Diverse aspects of biomedical engineering, from basic mechanobiology to the design of novel biomaterials, medical devices, and surgical interventions. Prerequisites: PHYS 180, 181, MATH 115, and ENAS 194. QR

* **BENG 355La, Physiological Systems Laboratory** Rong Fan
Introduction to laboratory techniques and tools used in biomedical engineering for physiological measurement. Topics include bioelectric measurement, signal processing, and dialysis. Enrollment limited to majors in Biomedical Engineering, except by permission of the director of undergraduate studies. SC ½ Course cr

* **BENG 356Lb, Biomedical Engineering Laboratory** Tarek Fahmy
Continuation of BENG 355L, introducing laboratory techniques and tools used in biomedical engineering. Topics include image processing, ultrasound, and microscopy. Enrollment limited. SC ½ Course cr

* **BENG 405b / EVST 415b, Biotechnology and the Developing World** Anjelica Gonzalez
Study of technological advances that have global health applications. Ways in which biotechnology has enhanced quality of life in the developing world. The challenges of implementing relevant technologies in resource-limited environments, including technical, practical, social, and ethical aspects. Prerequisite: MCDB 120, or BIOL 101 and 102.

* **BENG 406b, Medical Software Design** Xenophon Papademetris
Software design and implementation for medical applications, with emphasis on how new ideas can be developed within today's healthcare regulatory environment. This project-based course focuses on the interaction of medical imaging and 3D printing. Topics include the methods and design principles to take 3D medical images, and how to image analysis algorithms to create 3D models to guide diagnosis and interventional procedures or build patient-specific medical devices. Permission of the instructor. Strong programming background in at least one programming language. SC

* **BENG 410a, Physical and Chemical Basis of Bioimaging and Biosensing** Douglas Rothman and Fahmeed Hyder
Basic principles and technologies for sensing the chemical, electrical, and structural properties of living tissues and of biological macromolecules. Topics include magnetic resonance spectroscopy, microelectrodes, fluorescent probes, chip-based biosensors, X-ray and electron tomography, and MRI. Prerequisites: BENG 351 and 352 or permission of instructor. QR, SC

BENG 411b, BioMEMS and Biomedical Microdevices Rong Fan
Principles and applications of micro- and nanotechnologies for biomedicine. Approaches to fabricating micro- and nanostructures. Fluid mechanics, electrokinetics, and molecular transport in microfluidic systems. Integrated biosensors and microTAS for laboratory medicine and point-of-care uses. High-content technologies, including DNA, protein microarrays, and cell-based assays for differential diagnosis and disease stratification. Emerging nanobiotechnology for systems medicine. Prerequisites: CHEM 161, 165, or 167 (or CHEM 112, 114, or 118), and ENAS 194. SC

* **BENG 422a, Engineering and Biophysical Approaches to Cancer** Michael Mak
This course focuses on engineering and biophysical approaches to cancer. The course examines the current state of the art understanding of cancer as a complex disease and the advanced engineering and biophysical methods developed to study and treat this disease. All treatment methods are covered. Basic quantitative and computational backgrounds are required. Prerequisites: BENG 249 or equivalent, MATH 120 or equivalent. QR, SC

BENG 434a, Biomaterials Anjelica Gonzalez
Introduction to the major classes of biomedical materials: ceramics, metals, and polymers. Their structure, properties, and fabrication connected to biological applications, from implants to tissue-engineered devices and drug delivery systems. Prerequisite: CHEM 165 (or CHEM 113 or 115); organic chemistry recommended. SC

* **BENG 435b, Biomaterial-Tissue Interactions** Themis Kyriakides
Study of the interactions between tissues and biomaterials, with an emphasis on the importance of molecular- and cellular-level events in dictating the performance and longevity of clinically relevant devices. Attention to specific areas such as biomaterials for tissue engineering and the importance of stem/progenitor cells, as well as biomaterial-mediated gene and drug delivery. Prerequisites: CHEM 161, 165, or 167 (or CHEM 112, 114, or 118); MCDB 120, or BIOL 101 and 102; or equivalents. SC

BENG 444a, Fundamentals of Medical Imaging Chi Liu, Dana Peters, and Gigi Galiana
Review of basic engineering and physical principles of common medical imaging modalities including X-ray, CT, PET, SPECT, MRI, and echo modalities (ultrasound and optical coherence tomography). Additional focus on clinical applications and cutting-edge technology development. BENG 352 or similar background. QR, SC

[BENG 445, Biomedical Image Processing and Analysis]

BENG 449b, Biomedical Data Analysis Richard Carson
Study of biological and medical data analysis associated with applications of biomedical engineering. Provides basics of probability and statistics, as well as analytical approaches for determination of quantitative biological parameters from experimental data. Includes substantial programming in MATLAB. Prerequisite: MATH 120 or ENAS 151. After or concurrently with ENAS 194. QR

BENG 455b, Vascular Mechanics Jay Humphrey
Methods of continuum biomechanics used to study diverse vascular conditions and treatments from an engineering perspective. Topics include hypertension, atherosclerosis, aneurysms, vein grafts, and tissue engineered constructs. Emphasis on mechanics driven by advances in vascular mechanobiology. Prerequisite: BENG 353. QR

* **BENG 456b, Molecular and Cellular Biomechanics** Michael Murrell
The basic mechanical principles at the molecular and cellular level that underlie the major physical behaviors of the cell, from cell division to cell migration. Basic cellular physiology, methodology for studying cell mechanical behaviors, models for understanding the cellular response under mechanical stimulation, and the mechanical impact on cell differentiation and proliferation. Prerequisites: MENG 211 and 280 or equivalents, and experience with MATLAB. Recommended preparation: BENG 353 and MCDB 205. QR, SC

BENG 458b, Multiscale Models of Biomechanical Systems Stuart Campbell
Current methods for simulating biomechanical function across biological scales, from molecules to organ systems of the human body. Theory and numerical methods; case studies exploring recent advances in multiscale biomechanical modeling. Includes computer laboratory sessions that introduce relevant software packages. Prerequisites: BENG 249, 351, and 353, or permission of instructor. QR

BENG 459a / MENG 459a, Neuromuscular Biomechanics Madhusudhan Venkadesan
Mechanics and control of animal movement, including skeletal muscle mechanics, systems-level neural and sensory physiology, elements of feedback control, and optimal control. Deriving equations of motion for multibody mechanical systems that are actuated by muscles or muscle-like motors; incorporating sensory feedback; analyzing system properties such as stability and energetics. Prerequisites: MENG 383 and MATH 222 or equivalents, and familiarity with MATLAB or a similar scientific computing environment. QR RP

BENG 463a / CENG 320, Immunoengineering Tarek Fahmy
Introduction to immunoengineering, a field combining immunology with the physical sciences and engineering. Focus on biophysical principles and biomaterial applications for understanding and engineering immunity. SC

BENG 465b / MB&B 361b / MCDB 361b / NSCI 325b, Dynamical Systems in Biology Thierry Emonet and Jonathon Howard
Advanced topics related to dynamical processes in biological systems. Processes by which cells compute, count, tell time, oscillate, and generate spatial patterns. Time-dependent dynamics in regulatory, signal-transduction, and neuronal networks; fluctuations, growth, and form. Comparisons between models and experimental data. Dynamical models applied to neurons, neural systems, and cellular biophysical processes. Use of MATLAB to create models. Prerequisite: MCDB 330 or equivalent, or a 200-level biology course, or with permission of instructor. QR

BENG 467b, Systems Biology of Cell Signaling Andre Levchenko
Approaches from systems biology to the fundamental processes underlying both the sensory capability of individual cells and cell-to-cell communication in health and disease. Prerequisites: BENG 249 and ENAS 194, or equivalents. QR, SC

* **BENG 471a and BENG 472b, Special Projects** James Duncan
Faculty-supervised individual or small-group projects with emphasis on research (laboratory or theory), engineering design, or tutorial study. Students are expected to consult the director of undergraduate studies and appropriate faculty members about ideas and suggestions for suitable topics. This course, offered Pass/Fail, can be taken at any time during a student's career, and may be taken more than once. For the Senior Project, see BENG 473, 474. Permission of both the instructor and the director of undergraduate studies is required.

* **BENG 473a and BENG 474b, Senior Project** James Duncan
Faculty-supervised biomedical engineering projects focused on research (laboratory or theory) or engineering design. Students should consult with the director of undergraduate studies and appropriate faculty mentors for suitable projects. BENG 473 is taken during the fall term of the senior year and BENG 474 is taken during the spring term of the senior year. Permission of both the faculty mentor and the director of undergraduate studies is required.

BENG 475a / CPSC 475a / EENG 475a, Computational Vision and Biological Perception Steven Zucker
An overview of computational vision with a biological emphasis. Suitable as an introduction to biological perception for computer science and engineering students, as well as an introduction to computational vision for mathematics, psychology, and physiology students. Prerequisite: CPSC 112 and MATH 120, or with permission of instructor. QR, SC RP

BENG 476b / CPSC 476b, Advanced Computational Vision Steven Zucker
Advanced view of vision from a mathematical, computational, and neurophysiological perspective. Emphasis on differential geometry, machine learning, visual psychophysics, and advanced neurophysiology. Topics include perceptual organization, shading, color and texture analysis, and shape description and representation. After CPSC 475. QR, SC

* **BENG 480a, Seminar in Biomedical Engineering** Andre Levchenko
Oral presentations and written reports by students analyzing papers from scientific journals on topics of interest in biomedical engineering, including discussions and advanced seminars from faculty on selected subjects. (For Class of 2020 and beyond this course is worth .5 credit.)

* **BENG 485b, Fundamentals of Neuroimaging** Fahmeed Hyder and Douglas Rothman
The neuroenergetic and neurochemical basis of several dominant neuroimaging methods, including fMRI. Technical aspects of different methods, interpretation of results, and controversies or challenges regarding the application of fMRI and related methods in medicine.
WR, SC