BIOMEDICAL ENGINEERING

Director of undergraduate studies: Lawrence H. Staib (lawrence.staib@yale.edu), N309 B TAC, 785-5958; seas.yale.edu/departments/biomedical-engineering

Engineering methods and strategies are used to address biomedical problems ranging from studies of physiological function using images to the development of novel drug delivery methods and new biomaterials. The B.S. degree in Biomedical Engineering is designed to provide students with an understanding of common fundamental methodologies in biomedical engineering and the ability to develop quantitative approaches to one of four biomedical engineering concentrations: Bioimaging, Biomechanics and Mechanobiology, Biomolecular Engineering, and Systems Biology. The course structure of the major permits students to bridge basic concepts in the life sciences and traditional areas of engineering, while gaining a comprehensive understanding of biomedical engineering as a field of study. The program provides graduates with an excellent background for graduate study in biomedical engineering and related areas, or in medicine and other health professions as well as for a diverse range of careers in industry, consulting, or government.

PREREQUISITES

The following prerequisites are common to all concentrations in the major: BIOL 101 and 102 or a higher-level course in MCDB or MB&B, with the permission of the director of undergraduate studies (DUS); a lecture course in chemistry numbered CHEM 161 or higher; MATH 115 or 116 (not necessary if placed into MATH 120 or ENAS 151); MATH 120 or ENAS 151; ENAS 194; PHYS 180, 181 and PHYS 205L, 206L or PHYS 165L, 166L. Students with advanced high school preparation may move ahead to more advanced courses with DUS permission.

REQUIREMENTS OF THE MAJOR

Students must complete thirteen term courses, totaling at least eleven course credits, beyond the prerequisites, including at least three required courses in the chosen concentration and the senior requirement (see below). During the first two years, students study basic biology, chemistry, mathematics, and physics (see prerequisites). By the end of the sophomore year, students should have taken BENG 280, 249, and 350. In the junior year, students gain a comprehensive grounding in the field through BENG 351, 352, 353, 355L, and 356L. During the junior and senior years, students acquire depth by taking electives in one of the four concentrations. One relevant course (e.g. MB&B 300) may be substituted with DUS permission. A senior seminar (BENG 480) provides information about the field and a senior project (BENG 474 or BENG 473, 474) allows students to explore an area in depth.

Students in all concentrations are required to take the following courses: BENG 249, 280, 350, 351, 352, 353, 355L, 356L, and 480.

Students in the *Bioimaging concentration* (YC BENG: Bioimaging) must also take three courses chosen from, e.g., BENG 404, 406, 410, 444, 445, 449, 475, 476, or 485.

Students in the *Biomechanics and Mechanobiology concentration* (YC BENG: Biomchncs&Mchnbiology) must also take three courses chosen from, e.g., MENG 185, 361, BENG 404, 406, 410, 422, 456, or 458.

Students in either the **Biomolecular Engineering concentration** (YC BENG: Biomolecular Engrng) and the **Systems Biology concentration** (YC BENG: Systems Biology) must also take three courses chosen from, e.g., BENG 404, 406, 410, 411, 422, 435, 463, 465, 467, 468, 469, 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.

Searchable Attributes YC BENG: Bioimaging, YC BENG: Biomchncs&Mchnbiology, YC BENG: Biomolecular Engrng, YC BENG: Systems Biology

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

SENIOR REQUIREMENT

In their sophomore year, all students must enroll in BENG 280 and in their senior year, all students must enroll in BENG 480; both are half-credit courses. 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.

Combined B.S./M.S. degree program Exceptionally able and well-prepared students may apply to complete a course of study leading to the simultaneous award of the B.S. and M.S. degrees after eight terms of enrollment. See Academic Regulations, section L, Special Academic Arrangements, "Simultaneous Award of the Bachelor's and Master's Degrees." Interested students should consult the DUS prior to the sixth term of enrollment for specific requirements in Biomedical Engineering.

SUMMARY OF MAJOR REQUIREMENTS

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 or 116 (not necessary if placed into MATH 120 or ENAS 151); MATH 120 or ENAS 151; PHYS 180, 181 and PHYS 205L, 206L or PHYS 165L, 166L.

Number of courses 13 term courses, totaling at least 11 course credits, beyond prerequisites (incl senior req)

Specific courses required *All concentrations*—BENG 249, 280, 350, 351, 352, 353, 355L, 356L, 480

Distribution of courses *All concentrations*—see above for suggested courses for each concentration

Substitution permitted Relevant course with DUS permission

Senior requirement BENG 280, a half-credit course taken sophomore year**;** BENG 480, a half-credit course taken senior year; a one-term senior project in final term of enrollment (BENG 474) or two-term, yearlong senior project (BENG 473 and 474)

FACULTY OF THE DEPARTMENT OF BIOMEDICAL ENGINEERING

Professors †Helene Beneviste, †Joerg Bewersdorf, Richard Carson, †Nicholas Christakis, †Todd Constable, †Robin de Graaf, James Duncan, Rong Fan, †Henry Hsia, Jay Humphrey, Fahmeed Hyder, Themis Kyriakides, †Francis Lee, Andre Levchenko, †Graeme Mason, †Evan Morris, †Xenophon Papademetris, Douglas Rothman, Mark Saltzman, †Martin Schwartz, †Frederick Sigworth, †Albert Sinusas, †Brian Smith, Lawrence Staib, †Hemant Tagare, †Paul Van Tassel, Steven Zucker

Associate Professors Stuart Campbell, Tarek Famy, †Gigi Galiana, Anjelica Gonzalez, †Michelle Hampson, Farren Isaacs, †Chi Liu, Kathryn Miller-Jensen, Michael Murrell, †Dana Peters, †Dustin Scheinost, †Jiangbing Zhou

Assistant Professors †Daniel Coman, †Nicha Dvornek, †Ansel Hillmer, Michael Mak, Christina Rodriquez, Gregory Tietjen, †Daniel Wiznia

Research Scientist †Steven Tommasini

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 230a / MB&B 330a / MCDB 330a / NSCI 324a, Modeling Biological Systems I Thierry Emonet and Kathryn Miller-Jensen
Biological systems make sophisticated decisions at many levels. This course explores the molecular and computational underpinnings of how these decisions are made, with a focus on modeling static and dynamic processes in example biological systems. This course is aimed at biology students and teaches the analytic and computational methods needed to model genetic networks and protein signaling pathways. Students present and discuss original papers in class. They learn to model using MatLab in a series of in-class hackathons that illustrate the biological examples discussed in the lectures. Biological systems and processes that are modeled include: (i) gene expression, including the kinetics of RNA and protein synthesis and degradation; (ii) activators and repressors; (iii) the lysogeny/lysis switch of lambda phage; (iv) network motifs and how they shape response dynamics; (v) cell signaling, MAP kinase networks and cell fate decisions; and (vi) noise in gene expression. Prerequisites: MATH 115 or 116.

BIOL 101-104, or with permission of instructors. This course also benefits students who have taken more advanced biology courses (e.g. MCDB 200, MCDB 310, MB&B 300/301).   QR, SC   0 Course cr

BENG 249b, Introduction to Biomedical Computation   Staff
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   0 Course cr

* BENG 280a, Sophomore Seminar in Biomedical Engineering   Cristina Rodriguez
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   Staff
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   0 Course cr

BENG 351b / CENG 351b, Biotransport and Kinetics   Staff
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   0 Course cr

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   0 Course cr

* BENG 355La, Physiological Systems Laboratory   Staff
Introduction to laboratory techniques and tools used in biomedical engineering for physiological measurement. Topics include bioelectric measurement, signal processing,

and bone mechanics. Enrollment limited to majors in Biomedical Engineering, except by permission of the director of undergraduate studies.   SC   0 Course cr

* BENG 356Lb, Biomedical Engineering Laboratory   Staff
Continuation of BENG 355L, introducing laboratory techniques and tools used in biomedical engineering. Topics include biomaterials and cell interactions, magnetic resonance spectroscopy and imaging, and image processing and machine learning. Enrollment limited.   SC   0 Course cr

* BENG 403b / ECON 463b, The Economics and Science of Medicine   Gregory Raskin and Yashodhara Dash
This multidisciplinary class is an exploration of the background of today's bestselling medicines, their huge commercial impact, and the companies that created them. It focuses on the most compelling aspects of drug development and company formation in the context of topical issues like cancer treatment, gene editing, stem cell therapy, the opioid epidemic, and drug pricing controversies. Prerequisite: Introductory or intermediate microeconomics, introductory or intermediate Biology, Molecular Biology, Chemistry or Biomedical Engineering.   SO

BENG 404b / MENG 404b, Medical Device Design and Innovation   Daniel Wiznia
The engineering design, project planning, prototype creation, and fabrication processes for medical devices that improve patient conditions, experiences, and outcomes. Students develop viable solutions and professional-level working prototypes to address clinical needs identified by practicing physicians. Some attention to topics such as intellectual property, the history of medical devices, documentation and reporting, and regulatory affairs.   0 Course cr

* 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 is a project-based class. The lectures provide essential material to help the students successfully complete their projects. In particular, the lectures cover material in the following three broad areas: (i) Medical software design based on a clinical need. (ii) Needs identification, verification, validation, and overview of the FDA regulatory process. (iii) Introductory material in experimental design, image analysis, and machine learning as needed by the projects. We also examine the new proposed FDA regulations on the use of machine learning in medical devices and related issues related to the use of these techniques in medical software in general. Prerequisite: Some programming background in at least one programming language. Instructor permission required.

* BENG 410a, Physical and Chemical Basis of Bioimaging and Biosensing   Douglas Rothman and Ansel Hillmer
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 415a / ENAS 415a, Practical Applications of Bioimaging and Biosensing
      Daniel Coman, Ansel Hillmer, and Evelyn Lake
Detecting, measuring, and quantifying the structural and functional properties of tissue is of critical importance in both biomedical research and medicine. This course focuses on the practicalities of generating quantitative results from raw bioimaging and biosensing data to complement other courses focus on the theoretical foundations which enable the collection of these data. Participants in the course work with real, cutting-edge data collected here at Yale. They become familiar with an array of current software tools, denoising and processing techniques, and quantitative analysis methods that are used in the pursuit of extracting meaningful information from imaging data. The subject matter of this course ranges from bioenergetics, metabolic pathways, molecular processes, brain receptor kinetics, protein expression and interactions to wide spread functional networks, long-range connectivity, and organ-level brain organization. The course provides a unique hands-on experience with processing and analyzing *in vitro* and *in vivo* bioimaging and biosensing data that is relevant to current research topics. The specific imaging modes which are covered include *in vivo* magnetic resonance spectroscopy (MRS) and spectroscopic imaging (MRSI), functional, structural, and molecular imaging (MRI), wide-field fluorescent optical imaging, and positron emission tomography (PET). The course provides the necessary background in biochemistry, bioenergetics, and biophysics for students to motivate the image manipulations which they learn to perform. Prerequisites: Math through first order differential equations, PHYS 180/181, CHEM 161, BIOL 101/102, BENG 249 or other experience with scientific software like MATLAB®, BENG 350 and BENG 410 (both of which can be taken at the same time as this course)   sc   0 Course cr

* 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 424b, Topics in Computational and Systems Biology   Purushottam Dixit
This course covers topics related to modeling biological networks across time and length scales. Specifically, the course covers models of intracellular signaling networks, transcriptional regulation networks, cellular metabolic networks, and ecological networks in microbial consortia. For each type of network, we cover the biological basics, standard mathematical treatments including deterministic and stochastic modeling, methods to infer model parameters from data, and new machine-learning based inference approaches. The required mathematical methods are briefly covered. The course assignments involve coding in MATLAB. Prerequisite: MATH 120 or ENAS 151.

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, Modern Medical Imaging: Lecture and Demonstrations   Chi Liu, Dana
    Peters, and Gigi Galiana
Survey of engineering and physics foundations of modern medical imaging modalities with an emphasis on immersive and interactive experiences. Traditional lectures are balanced with guest lectures on state-of-the-art techniques and opportunities to observe procedures, acquire imaging data and reconstruct images. Modalities include MRI, X-ray, CT, SPECT, PET, optical and ultrasound methods. Prerequisite: BENG 352 or similar background.   QR, SC

[**BENG 445, Biomedical Image Processing and Analysis**]

BENG 449b, Biomedical Data Analysis   Staff
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   0 Course cr

[**BENG 456, Molecular and Cellular Biomechanics**]

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 463a, Immunoengineering   Tarek Fahmy
Immuno-engineering uses engineering and applied sciences to better understand how the immune system works. It also uses immunity to build better models and biomaterials that help fight diseases such as cancer, diabetes, lupus, MS, etc. This is an integrative class. It integrates what we know in ENAS with what we know in Immunity to address critical and urgent concerns in health and disease. Students learn that analytical tools and reagents built by engineers address some extremely significant problems in immunity, such as optimal vaccine design. Students also have the opportunity to apply new understandings towards gaping holes in immunotherapy

and immunodiagnostics. Prerequisite: A basic understanding of biochemistry, biophysics, cell biology; calculus and differential equations.   QR, SC

BENG 465b / MB&B 361b / MCDB 361b / NSCI 325b, Modeling Biological Systems II   Thierry Emonet

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 466b, Engineering of Drug Delivery   W. Mark Saltzman

Approaches and technologies for getting pharmaceutical agents into particular cells and tissues in the body for a biological effect, while minimizing unwanted toxic or side effects. Mathematical descriptions of the biological barriers to drug delivery, such as diffusion, permeation through membranes, and lifetime of circulation; engineering design to improve drug delivery. Prerequisites: ENAS 194 and BENG 351 or equivalents.   SC

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 468b, Topics in ImmunoEngineering   Tarek Fahmy

This course addresses the intersection of Immunobiology with Engineering and Biophysics. It invokes engineering tools, such as biomaterials, solid-state devices, nanotechnology, biophysical chemistry, and chemical engineering towards developing newer and effective solutions to cancer immunotherapy, autoimmune therapy, vaccine design, transplantation, allergy, asthma, and infections. The central theme is that dysfunctional immunity is responsible for a wide range of disease states and that engineering tools and methods can forge a link between the basic science and clinically translatable solutions that will potentially be "modern cures" to disease. This course is a follow-up to BENG 463, Immunoengineering and focuses more on the clinical translation aspect as well as new understandings in immunology and how they can be translated to the clinic and eventually to the market. Prerequisites: BENG 463, Differential Equations, Advanced Calculus.   SC

* BENG 471a and BENG 472b, Special Projects   Lawrence Staib

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   Lawrence Staib

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   Cristina Rodriguez

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.)   ½ Course cr

* 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