

Biomedical Engineering

The usefulness of the methods of engineering science for solving biological and medical problems has become increasingly evident in recent years. The application of engineering to these problems is known as biomedical engineering. Some examples of biomedical engineering include instrumentation and systems for use in medical environments, health care delivery systems, therapeutic and prosthetic devices such as artificial organs and orthopedic implants, and the application of quantitative methods and engineering-based modeling to basic research in the biological sciences.

The Department of Biomedical Engineering offers three programs of study to prepare students to work in this area: an undergraduate program leading to a bachelor's degree with a choice of B.S. and B.A., a master's degree program, and a doctoral degree program.

Research in the department focuses on several general areas: biomaterials, biomedical imaging systems, biomedical sensors and instrumentation, cardiovascular systems physiology, molecular and cellular systems physiology, systems neurobiology, theoretical and computational biology, cell and tissue engineering, and nanobiotechnology.

The Faculty

Robert H. Allen, Associate Research Professor: design, education, birth mechanics.

Joel Bader, Assistant Professor: bioinformatics and computational biology.

Michael A. Beer, Assistant Professor: genomics and computational molecular biology.

Henry Colecraft, Assistant Professor: molecular biology and physiology of voltage-gated calcium channels, viral gene delivery, gene therapy, animal models of cardiovascular and neurological diseases.

Jennifer H. Elisseeff, Assistant Professor: tissue engineering, biomaterials, cartilage regeneration.

Harry R. Goldberg, Assistant Professor, Assistant Dean School of Medicine: interactive simulations, virtual classrooms.

Eileen Haase, Instructor: Models for Life, Physiological Foundations Laboratory, Cellular and Tissue Engineering Laboratory.

Richard J. Johns, University Distinguished Service Professor: industrial liaison.

Scot C. Kuo, Associate Professor: cell motility and mechanics, nanoscale biophysics, laser-based bioinstrumentation.

Kam W. Leong, Professor: protein and gene delivery, tissue engineering, polymeric biomaterials.

Andre Levchenko, Assistant Professor: intracellular signal transduction, cell engineering, cancer research.

Homayoun Mozaffari, Research Associate: surgical assist devices.

Michael I. Miller, Professor: image understanding, computer vision, medical imaging, computational linguistics, computational neuroscience.

Baohan Pan, Research Associate: nerve regeneration, spinal cord injury, spinal cord regeneration.

Aleksander S. Popel, Professor: physiological flows and molecular transport, microcirculation, cell mechanics.

J. Tilak Ratnanather, Assistant Research Professor: computational anatomy, biomedical imaging, numerical analysis, mathematical biology of the cochlea.

Murray B. Sachs, Professor (Chair): auditory neurophysiology and psychophysics.

Lawrence P. Schramm, Professor: spinal cord injury and regeneration, neural regulation of the circulation.

Reza Shadmehr, Professor: human motor control and learning in health and disease, functional imaging of the brain, human neurophysiology, computational and theoretical neuroscience.

David L. Sherman, Research Assistant Professor: neurological signal processing, seizure propagation in animal models of epilepsy.

Artin A. Shoukas, Professor: systems analysis of circulatory systems, systems physiology.

Alexander A. Spector, Associate Research Professor: biosolid mechanics, cell mechanics, molecular motors, mathematical and computational modeling.

Nitish V. Thakor, Professor: medical instrumentation and medical micro and nanotechnologies, neurological instrumentation, signal processing, computer applications.

Leslie Tung, Associate Professor: functional electrophysiology of cultured cardiac cell networks, cardiac arrhythmias, analysis of multicellular structure.

Rene Vidal, Assistant Professor: computer vision (human motion, dynamic scene reconstruction, multiple view geometry, omnidirectional vision), machine learning (generalized component analysis and geometric clustering), robotics (vision-based control), control (identification of hybrid systems).

Xiaoqin Wang, Associate Professor: neurophysiology of the auditory cortex, neural mechanisms of speech perception and learning, computational neuroscience.

Raimond L. Winslow, Professor: computational biology, cardiac electrophysiology.

Kevin J. Yarema, Assistant Professor: metabolic engineering of oligosaccharide biosynthetic pathways, analysis of the effects of unnatural metabolites on gene expression, glycobiology.

Eric D. Young, Professor: auditory neurophysiology, neural modeling, sensory processes.

David T. Yue, Professor: ionic channel electrophysiology, biophysics, molecular biology.

Kechen Zhang, Assistant Professor: theoretical neuroscience, computational neuroscience, neural computation.

Joint, Part-Time, and Visiting Appointments

Andreas G. Andreou, Professor (Electrical and Computer Engineering): electron devices, VLSI sensors, micropower electronics, physics of information processing.

Ergin Atalar, Professor (Radiology, Electrical and Computer Engineering): magnetic resonance imaging, interventional MRI, design and development of MR compatible devices.

Isaac N. Bankman, Assistant Professor (Applied Physics Laboratory): biomedical signal and image processing.

Ronald D. Berger, Associate Professor (Cardiology): mechanisms of sudden cardiac death, new modalities of ablation therapy, device development, signal processing.

Dan E. Berkowitz, Associate Professor (Anesthesiology and Critical Care Medicine): molecular mechanisms of cardiovascular deconditioning in rodent models of microgravity, vasoregulatory dysfunction associated with obesity, diabetes, the role of leptin in vasoregulatory changes.

Paul A. Bottomley, Professor (Radiology): magnetic resonance imaging and spectroscopy, medical imaging.

Charles C. Della Santina, Assistant Professor (Otolaryngology): electrical stimulation of the vestibular system for restoring balance function, vestibular function testing.

Andrew S. Douglas, Associate Dean and Professor (Mechanical Engineering): nonlinear solid mechanics, soft tissue mechanics, mechanics of active materials.

Paul A. Fuchs, Professor (Otolaryngology): biophysics of sensory hair cell, regulation of ion channel expression.

Donald Geman, Professor (Applied Mathematics and Statistics): mathematical imaging, statistical learning, visual recognition, computational genomics.

John Goutsias, Professor (Electrical and Computer Engineering): digital processing, image processing and analysis.

Henry R. Halperin, Professor (Medicine): cardiovascular medicine, MR compatible devices.

Justin Hanes, Associate Professor (Primary: Chemical and Biomolecular Engineering; Secondary: The Sidney Kimmel Comprehensive Cancer Center): synthesis of new biodegradable polymers, targeted drug and gene delivery via the blood and inhalation, particle transport and trafficking in biological barriers, cancer.

Kalina Hristova, Assistant Professor (Materials Science and Engineering): biomolecular materials, biomembranes, biosensor development.

Steven S. Hsiao, Associate Professor (Neuroscience): neurophysiology of the central nervous system.

Pablo A. Iglesias, Professor (Electrical and Computer Engineering): linear control, H-infinity control, linear systems theory.

Kenneth O. Johnson, Professor (Neuroscience): neurophysiological study of the somato-sensory system.

David A. Kass, Professor (Cardiology): cardiac mechanics, ventricular arterial interaction and heart failure.

Konstantinos Konstantopoulos, Assistant Professor (Chemical and Biomolecular Engineering): cell and fluid mechanics in medical applications, cancer metastasis, thrombosis, inflammation/bacterial infection.

Hai-Quan Mao, Assistant Professor (Materials Science and Engineering): non-viral gene delivery, cell-materials interaction, polymeric scaffolds, design and synthesis of biodegradable polymeric materials.

Eduardo Marban, Professor (Cardiology): molecular and cellular biology of the heart in health and disease.

W. Lowell Maughan, Professor (Medicine): left ventricular function.

Elliot McVeigh, Associate Professor (NIH): magnetic resonance imaging.

Richard A. Meyer, Professor (Applied Physics Laboratory): neural mechanisms of pain, applications of technology to neuroscience problems.

Robert E. Miller, Associate Professor (Lab Medicine): clinical laboratory instrumentation, laboratory information systems.

- Lloyd B. Minor**, Professor (Otolaryngology-Head and Neck Surgery): vestibular neurophysiology. Vincent L. Pisacane, Associate Professor (United States Naval Academy): space technology, technology management.
- Carey E. Priebe**, Professor (Applied Mathematics and Statistics): statistics, image analysis, nonparametric estimation.
- Jerry L. Prince**, Professor (Electrical and Computer Engineering): multi-dimensional signal processing, medical imaging, computational geometry.
- Mark J. Shelhamer**, Associate Professor (Otolaryngology): nonlinear dynamics, vestibular and oculomotor modeling, space flight adaptation.
- Kathleen J. Stebe**, Professor (Chemical and Biomolecular Engineering): Marangoni effects, surfactant adsorption dynamics, mono-layer penetration by proteins and surfactants, protein adsorption and surface phase behavior, electroporation of biomembranes, dynamic surface tension.
- Robert H. Stiefel**, Instructor (Johns Hopkins Hospital): clinical engineering.
- Sean Sun**, Assistant Professor (Mechanical Engineering): biological force generation, molecular motors, cell motility, statistical mechanics of soft condensed materials.
- Tza-Huei (Jeff) Wang**, Assistant professor (Mechanical Engineering): micro/nanoscience and technology, BioMEMS, single molecule manipulation and detection.
- Ursula Wesselmann**, Associate Professor (Neurology): pathophysiological mechanisms of pelvic and urogenital pain, pain modulation during pregnancy and labor, gender differences in pain perception.
- Thomas B. Woolf**, Assistant Professor (Physiology): molecular dynamics calculations, membrane biophysics, computational neurosciences.
- Laurent Younes**, Associate Professor (Applied Mathematics and Statistics): statistical properties of Markov random fields, image analysis, deformation analysis—shape recognition.

Program Directors

The members of the Committee on Biomedical Engineering, which directs the Ph.D. degree program, are Professor Winslow (chair and director of the doctoral program), Professor Fuchs, Professor Johns, Professor Johnson, Professor Sachs, Professor Schramm, and Assistant Professor Mori. The director of the master's degree program is Professor Leong. The directors of the undergraduate program are Professor Popel and Professor Shoukas.

Facilities

The center of gravity for the Department of Biomedical Engineering is the Traylor and Ross research buildings on the campus of the School of Medicine. This location favors a close association with other basic medical science programs and provides access to the clinical environment of one of the nation's top-ranked hospitals. In June 2001 Clark Hall opened its doors on the Homewood campus to house the Whitaker Biomedical Engineering Institute. The Whitaker Institute has been established as a vital link between the School of Medicine and the Whiting School of Engineering. The vision of the institute is of an integrative research and education enterprise that will provide leadership in moving biomedical engineering to the forefront of biomedical science and practice.

The general facilities of the Department of Biomedical Engineering include seminar rooms that allow broadcasting throughout the university, physiology teaching laboratories, a microfabrication laboratory, a cell and tissue teaching and research laboratory, a library, a student instrumentation laboratory, a fully staffed mechanical shop and a supercomputing facility.

Each of the faculty members listed above further maintains a well-equipped laboratory for research in his/her area of interest. A wide variety of equipment in these laboratories is available to students as their interests draw them into active participation in research. For instance, there are three laboratories completely equipped for cardiovascular systems experimentation, including state-of-the-art equipment for measuring regional blood flows and pressures. At least four laboratories are equipped for the recording of activity from single and multiple neurons and for delivering complex, computer-generated, sensory stimuli to a variety of preparations. Four laboratories use computer-controlled systems to study muscle biophysics. Several laboratories collaborate with those of the Department of Materials Science and Engineering to provide complete instrumentation for both conventional and nondestructive testing and evaluation of biomaterials.

The profoundly interdivisional nature of biomedical engineering education at Johns Hopkins provides students with a wide range of general University facilities. These include the Welch Medical Library at the School of Medicine, the Eisenhower Library at the Homewood campus, the university computing facility, the Medical School Computing Center, and the Medical School's Microcomputer Laboratory.

Undergraduate Programs

The mission of the undergraduate program is to provide state-of-the-art biomedical engineering education to students in order that they may continue their education in graduate, medical, and professional schools or pursue careers in industry. To this end, our responsibility is as much to the future as it is to the present. Through a strong research and educational environment, we strive to empower our students to explore and define their own frontiers as well as instill the ethical principles that will foster rewarding professional endeavors.

The undergraduate program in biomedical engineering, which is accredited by the Accreditation Board for Engineering and Technology (ABET), provides a strong foundation in mathematics, engineering, and science. The program emphasizes preparation for advanced study in an area related to biomedical engineering and is broad enough to accommodate students who plan graduate work in biology, medicine, engineering, biophysics, physiology, or biomedical engineering.

Thus, the objective of the undergraduate program is to educate students majoring in biomedical engineering who:

- will be prepared to enter graduate (MS or PhD) or professional schools (Medical, Veterinarian, Business, Public Health, Law) or careers in biomedical engineering or a related field.
- will use and apply the necessary tools, scientific basics and fundamental knowledge of biomedical engineering.
- will pursue lifelong scientific inquiry, learning and creativity
- will have ability to communicate effectively, both orally and in written form, and to function successfully as members and/or leaders or diverse teams
- will understand the social, ethical, business, and technical context with which their contributions will be utilized.

The biomedical engineering program normally leads to the bachelor of science (B.S.) degree and requires at least 124.5 credits. The B.S. program is recommended for students who plan careers in engineering or who plan to attend graduate school in engineering. If a student wishes to take a more flexible program with less emphasis on engineering, a B.A. program is also available. Either the B.S. or the B.A. program can meet the needs of a student who plans graduate study in a nonengineering area.

Each student plans a curriculum suited to his/her goals, with the assistance of a faculty adviser. Upon completion of the B.S. in Biomedical Engineering, students will demonstrate the ability to:

- apply fundamental knowledge of mathematics, physical sciences, biology, physiology and engineering for the solution of problems at the interface of engineering and biology; the ability to make measurements on and interpret data from living systems, addressing the problems associated with the interaction between living and non-living materials and systems.
- use effective communication skills, work within multidisciplinary teams and have an awareness of professional and ethical responsibilities to have a positive impact on the global society
- recognize the importance of lifelong learning in order to expand knowledge
- participate in creative, synthetic, integrative activities of design courses and independent projects

The program also encourages individual study and research and gives academic credit for them. Students are welcome to work in laboratories on the Homewood campus or at the Medical Institutions.

Bachelor of Science in Biomedical Engineering

Students seeking the B.S. degree are encouraged to focus their studies on one of the traditional engineering disciplines (electrical, mechanical, materials, computers, or chemical) and its biomedical applications. If a student's program is sufficiently focused, a notation will be placed on the transcript stating an area of concentration within biomedical engineering. See the Biomedical Engineering Undergraduate Advising Manual for specifics on areas of concentration, lists of recommended mathematics and engineering electives, limitations on credits for courses with overlapping material, and the design content of engineering courses.

Requirements for the B.S. Degree

(See also General Requirements for Departmental Majors, page 46.)

The B.S. degree in Biomedical Engineering requires 124.5 credits. The courses listed below must either be taken or passed by examination for advanced credit. Engineering, science, and mathematics courses may not be taken satisfactory/ unsatisfactory. No more than 6 credits of engineering, science, or mathematics courses in which a grade of D was received may be counted.

Basic Sciences (21-22 credits):

- General physics with lab
- Introductory chemistry and organic chemistry with lab
- At least one semester of intermediate chemistry or intermediate organic chemistry

Mathematics (22 credits):

- Calculus I, II, III
- Linear algebra and differential equations
- At least one additional semester of advanced statistics

Humanities and Social Sciences (18 credits):

These courses should form a coherent program, relevant to the student's goals, with at least one course at the 300-level or higher. They should include:

- One course in which ethical and social issues related to technology are discussed.
- At least two semesters of (W) courses (see Writing Requirement, page 42).

Engineering Core (23 credits):

- 580.221 Molecules and Cells
- 580.222 Biomedical Signal and Dynamic Systems
- 580.421-422, 423-424 Physiological Foundations for Biomedical Engineering with lab. The 12 credits for the 580.421-424 courses count as 6 Engineering (E) credits and 6 Natural Science (N) credits (in Biology).
- 580.110 Models for Life or 580.111-112 BME Design Team
- 580.202 Biomedical Engineering in the Real World
- Two "core" engineering courses specific to the student's area of concentration

Engineering Electives (23-55 credits):

Additional courses in engineering must be taken, for a total of 46.5 or more credits of engineering. The program must include the following:

- At least 9 credits of biomedical engineering (580.xxx) courses at the 400-level or higher, not to include 580.421-424 or research or independent study.
- At least 3-4 credits of senior design experience.
- At least 4.5 credits of engineering laboratories, not to include 580.423-424.
- At least 31 credits of engineering science courses.
- At least 18 credits at the 300-level or higher.
- Up to 6 credits of independent study or research (580.5xx) may be applied toward engineering requirements.

- Students must gain some proficiency in computer programming as early as possible. This can be done by taking 600.107, 600.109, 500.200 or 510.408.

Sample B.S. Program

Biomedical engineering programs consist of courses drawn from one of the traditional engineering disciplines (chemical, computer, electrical, materials, or mechanics) and life sciences/ physiology, leading to advanced courses in biomedical applications in the junior and senior years. Sample programs are available on-line at <http://www.bme.jhu.edu/undergrad>. These samples illustrate the general sequence of courses; however, engineering electives may be substituted to coincide with a specific interest.

New B.S. Program

To Be Offered to Students Entering in 2005-2006

Several factors have led us to develop the new curriculum presented here.

- The evolution of biomedical engineering as a discipline in and of itself has allowed us to define a set of "core knowledge" that every graduate of our program should possess. Our new curriculum begins with a "Biomedical Engineering Core" required of all students, which provides this core knowledge.
- By organizing the students' choices of advanced engineering courses around biomedical engineering focus areas rather than traditional engineering disciplines, we can ensure both the depth of engineering education and the relevance to biological and medical problem solving.
- Because curriculum development and maintenance for each focus area will be the responsibility of faculty members with research interests appropriate to the area, all faculty members will be active participants in shaping the undergraduate curriculum.
- Finally, although graduates of our program have been known for their strong backgrounds in systems physiology, we believe that we should require them to become better educated in other "modern biology" areas such as genetics or developmental biology.

Core Knowledge

We consider the following to be areas of knowledge that must be part of the education of graduates of our program. Although it is unlikely that any student will become truly expert in all of the areas, we believe that their undergraduate education should make all of the areas accessible to the student in

the sense that after graduation from our program they will be able to understand and interpret the literature in any area of biomedical engineering intelligently and when necessary to continue to educate themselves in any area of the core.

- Molecular and cellular biology
- Engineering analysis of systems level biology and physiology
- Creating, analyzing and simulating a linear or non-linear system model from knowledge of the real biological system
 - Analysis of systems described by linear and non-linear ordinary differential equations
 - Analysis of biological control systems
- Fundamental thermodynamic principles in biology

The Biomedical Engineering Core

This set of core knowledge leads us to the following biomedical engineering core curriculum:

- 580.221: BME Molecular and Cellular Biology
- 580.222: Biological Systems and Control
- 580.223: Biological Models and Simulations (TBA course)
- 580.224: Thermodynamics and Statistical Physics for BME (TBA course)
- 580.421: Systems Bioengineering I with lab
 - Cells and Cardiovascular Systems
- 580.422: Systems Bioengineering II with lab
 - Neural Systems
- 580.425: Systems Bioengineering III – Genes to Cells (TBA course)

Biomedical Engineering Focus Areas

Building on the foundation of this core curriculum, each student is required to take a cohesive sequence of advanced engineering courses and at least one modern biology course, all appropriate to one of four Biomedical Engineering Focus Areas. A student's choice of Focus Area is made before the start of the junior year and is based on their experience with the Biomedical Engineering Core and their answers to the questions given below:

Biological Systems Engineering—“Do you want to focus on understanding at a fundamental level how biological systems work?”

Sensors, Micro/Nano Systems, and Instrumentation—“Do you want to build things that facilitate research or clinical medicine?”

Cell and Tissue Engineering and Biomaterials — “Do you want to create replacement cells, tissues and organs?”

Computational Bioengineering—“Do you want to focus on the use of mathematical theory or computers to solve very complex biological and medical problems?”

Advanced Engineering Sequences

Students are required to take at least 27 credits (nine courses) of advanced engineering appropriate to their focus area and to their specific interests within the area.

Focus Area Core: The student must take two from a selection of courses (six credits) prescribed by the focus area faculty as being fundamental to the focus area. One or both of these may be required of all students in the focus area. For example Dynamical Systems may be required of all biological systems focus area students, while students may choose a second course from among stochastic processes, information theory, or a number of similar courses.

Engineering Emphasis Sequence: The student must take 21 additional credits (seven courses) of advanced engineering electives, of which nine credits are in biomedical engineering courses and 12 are in other departments.

The courses from other departments are chosen from among a number of cohesive sequences suggested by the faculty or by the student with the approval of the adviser. For example, in the biological systems focus area, sequences might be defined that educate the student in areas such as signal processing, software engineering, hardware engineering and others. The principle here is that the student should obtain depth in some area of engineering appropriate to his/her interests. While we provide examples of such sequences, these are only a starting point for consideration by students and advisers.

The advanced biomedical engineering courses are chosen according to the student's interests in biomedical engineering problems. These courses require that the student integrate the core knowledge gained in the biomedical engineering core and in the engineering emphasis sequences to solve biomedical problems, and thus they form a “capstone” intellectual experience for the student. For example, a student interested in neuroscience problems might choose Theoretical Neuroscience, Models of the Neuron, and Biomechanics and Motor Control.

Modern Biology Electives

The student must choose at least one course appropriate to his/her interests and approved by the

adviser. For example, a student interested in neuroscience might take Development Biology and/or Molecular and Cellular Neuroscience.

Physics, Chemistry, Mathematics, and Humanities Requirements:

Physics	10 credits
Chemistry	12 credits
Math	24 credits
Humanities and Social Science	18 credits.

Additional information and sample programs will be available on the departmental Web site (www.bme.jhu.edu) in late fall, 2005.

Bachelor of Arts in Biomedical Engineering

Students seeking the B.A. degree postpone the choice of a concentration in biomedical engineering in order to obtain a broader undergraduate education. As compared to the B.S. degree, the B.A. degree calls for (1) 24 credits in the humanities and social sciences instead of 18, and a course cluster including one course on the advanced level, (2) four (W) courses instead of two (see Writing Requirement, page 40), and (3) at least two semesters of a modern foreign language.

Requirements for the B.A. Degree

(See also General Requirements for Departmental Majors, page 46.)

The B.A. in Biomedical Engineering requires 120 credits. The courses listed below must either be taken or passed by examination for advanced credit. See the Biomedical Engineering Undergraduate Advising Manual for lists of recommended courses, acceptable course substitutions, and limitations on credits for courses with overlapping material.

Basic Sciences (18 credits):

- General physics with lab
- Introductory chemistry with lab
- At least one semester of organic chemistry

Mathematics (20 credits):

- Calculus I, II, III
- Linear algebra and differential equations

Humanities and Social Sciences (24 credits):

These courses should form a coherent program, with at least 9 credits chosen from one department, including at least one 300-level course.

- At least four semesters of (W) courses.
- At least two semesters of a modern foreign language.

Engineering Core (32 credits):

- 580.221 Molecules and Cells
- 580.222 Biomedical Signal and Dynamic Systems
- 580.421-422, 423-424 Physiological Foundations for Biomedical Engineering with lab.
- Six credits of biomedical engineering (580.xxx) courses, not to include research or independent study. Cell Biology (020.306) may be substituted for three of these credits.
- Two “core” engineering courses

Engineering Electives:

At least 30 credits of courses coded (E) must be included. It is strongly recommended that 520.213 Circuits be taken before 580.421-424 Physiological Foundations. At least one semester of an engineering laboratory beyond 580.423-424 is recommended. A course in which the use of computers is emphasized is strongly recommended (e.g., 600.109 or 500.200).

Graduate Programs

Master of Science in Engineering

The master’s degree program is designed for students who wish to pursue careers in research and development, or as a step toward Ph.D. or M.D./Ph.D. education. The program, which is designed to be completed in two years, consists of core courses, elective courses, and a thesis project. The project may be basic research in a laboratory or practical engineering, related to patient monitoring or other clinical problems.

Admission and Financial Aid

Students with undergraduate degrees in engineering are eligible to apply. Exceptional students with degrees in basic sciences may also apply, but would normally have to take a number of courses to overcome deficiencies in their curriculum.

The M.S.E. program grants partial tuition fellowship awards on the basis of academic merit. Research assistantships are usually advertised by various laboratories in the institution to carry out specific research and development projects. Fellowships are also awarded to the top students in the program.

Application for admission must be received by January 10. Requests for applications should be addressed to the Director of the Biomedical Engineering Master’s Program, Clark Hall, 3400 North Charles Street, Baltimore, MD 21218. Information and downloadable applications are available online at <http://www.bme.jhu.edu/mse>.

Requirements for the M.S.E. Degree

Each student will take a minimum of 24 credits of courses at the 400-level or higher and complete a thesis. Students fulfill the course requirement by taking 580.421-422 Physiological Foundations for Biomedical Engineering and other advanced engineering courses. Students will also fulfill a minor teaching requirement by providing support to one of three lab-based undergraduate courses and two core lecture courses. Additionally, each student must complete a thesis based on a research problem requiring application of quantitative or applied engineering principles to biomedical engineering.

B.S./M.S.E. Program

Students enrolled in the B.S. Program in Biomedical Engineering may pursue a combined B.S./M.S.E. degree that can be completed in five years. Application for admission should be made no later than the spring semester of the junior year, and the course work should be carefully structured so as to fulfill all the requirements for the B.S. as well as the M.S.E. degree in a timely and coordinated manner. Students are advised to make an early start toward their master's thesis or internship. The Whiting School of Engineering awards partial tuition fellowships to outstanding undergraduate students in support of the graduate component of their studies.

Ph.D. in Biomedical Engineering

The purpose of the biomedical engineering doctoral program is to provide the fields of medicine and biology with a group of scientists having advanced training in the engineering sciences, physical sciences, and mathematics coupled with a thorough understanding of the basic biological sciences. This is accomplished by a combined curriculum that includes courses in the Schools of Arts and Sciences and Engineering and in the School of Medicine. Students are accepted with a variety of educational backgrounds and research objectives. The primary emphasis of the program is the application of the basic analytical tools of engineering science to fundamental research problems in biology (particularly mammalian physiology) and medicine.

Emphasis is placed on original research leading to the doctoral dissertation. The research is usually experimental in nature, and students are expected to learn biological experimental techniques; nevertheless, experiment or theory can be emphasized in the research as desired by the student. Many research opportunities are available within the department, located in the School of Medicine, but to keep the available research opportunities broad

and varied, students may work in the laboratories of investigators located throughout the Schools of Medicine, Arts and Sciences, or Engineering. To emphasize the interdisciplinary nature of the program, it is supervised by a committee composed of faculty members from both the Medical School and the Whiting School of Engineering.

Admission

Because many universities do not offer an undergraduate program in biomedical engineering, students planning graduate studies in this field should arrange a schedule to include courses beyond the elementary level in biology, mathematics, and the engineering sciences. However, it is recognized that many students discover their interest in biomedical engineering too late in their undergraduate career to complete such a program. Therefore, inquiries are invited from interested students who are prepared in any of the fields of engineering, physical sciences, or life sciences. The program accepts candidates only for the degree of doctor of philosophy.

Financial Aid

Fellowships for tuition and support stipends (regardless of citizenship or national origin) are available from the general funds of the University. US citizens and Permanent Residents are eligible for support from training grants from the National Institute of Health (NIH). Students are encouraged to apply for individual fellowships from the National Science Foundation and for NRSA awards from the NIH. Only on-line applications for admission are accepted and must be received by January 10. Notification of awards is made no later than April 1, and recipients are expected to signify their acceptance no later than April 15. Requests for applications or information should be addressed to the Director of the Biomedical Engineering Training Program, 606 Traylor Research Building, 720 Rutland Avenue, Baltimore, Maryland 21205.

Requirements for the Ph.D. Degree

The first two years are ordinarily devoted to advanced courses in engineering science and in biomedical science. Engineering, mathematics, and other physical science courses to be taken are arranged between students and their advisers. Each student is assigned a panel of three advisers during the first two years. Eighteen credit hours of course work in engineering, mathematics or physical sciences are required. In addition, students must complete eighteen credit hours of course work in the life sciences. Of these thirty six credit hours, at least six must be at the graduate level. At least three credit hours in

a course with strong engineering or mathematical theory content at the 600-level must be taken.

Summers are spent working in a biomedical laboratory to gain experience and to seek out a suitable thesis research area. By the beginning of the third year, students should start original research leading to the dissertation. Students must fulfill a modest teaching requirement during one year of their program. The remaining time is spent in thesis research. The program typically takes five to six years to complete.

The student must pass a preliminary oral examination which will be a Graduate Board examination. This is taken in the first half of the third year. The student must then conduct original research, describe it in a dissertation, and pass a final oral examination that is a defense of the dissertation. There is a minimum residency requirement of two consecutive academic years.

Integrated M.D./Ph.D. Program

Candidates for the Ph.D. in Biomedical Engineering who wish to apply jointly for the M.D. degree must apply directly through the School of Medicine. Although the combined programs would normally require at least seven years to execute sequentially, the combined program can ordinarily be completed in six years, with appropriate planning. Good preparation in biology and chemistry as well as mathematics, engineering, and the physical sciences is essential. Life science graduate requirements are met by the first year program of the School of Medicine. This program is more arduous than the Ph.D. program alone, but it may have marked advantage for students interested in clinical research and applications in hospital systems and in the delivery of health care. The catalog for the School of Medicine should be consulted for admissions requirements and procedures.

Undergraduate Courses

580.110 (E) Models for Life

This course introduces biomedical engineering freshmen to an orderly method for analyzing and modeling biological systems, using only corequisite freshman mathematics and physics. Working with an instructor in small groups, students will learn to develop mathematical models of biological systems and design the experiments necessary to test these models. Then, they will conduct experiments in small teams and compare their results with those predicted by their models. Students will learn the introductory computer skills necessary to simulate their mathematical models, analyze their experimental data, and plot their results. Freshman BME students taking physics or with physics AP credit only.

Haase 2 credits fall

580.111-112 (E,N) Design Team-Freshman

A two-semester course sequence where freshmen work with groups of BME upperclassmen mentors, and learn to use engineering principles to solve design problems that are biological, physiological, and/or medical. Freshmen are expected to use the informational content being taught in calculus, physics, and chemistry and apply this knowledge to the solution of practical problems encountered in biomedical engineering.

Allen 2 credits fall, 3 credits spring.

580.202 (E,S) Biomedical Engineering in the Real World

A series of weekly lectures to inform students about careers in biomedical engineering and to discuss technological, social, ethical, legal, and economic issues relevant to the profession. Topics include academic careers in biomedical engineering; biomedical engineering in industry (large corporations to sole entrepreneurship); health care delivery; ethical issues; legal issues (patenting, licensing, product liability); standards and government regulations;

and economic issues in biomedical engineering industry (start-up companies, global businesses).

Popel 1 credit spring

580.211-212 (E,N) Design Team-Sophomore

Sophomore-level version of 580.111-112. Permission of course directors required.

Allen 3 credits per semester

580.221 (N) Molecules and Cells

An introduction to modern molecular and cellular biology in the context of potential biomedical engineering applications. Topics covered: reactions between molecules, including receptor-ligand and antigen-antibody specificity, protein structure, enzyme catalysis, genetic information, protein processing and secretion, cell physiology and cell functions. Prerequisites: 030.101 Introductory Chemistry

Kuo, Colecraft 4 credits

580.222 (E) Biomedical Signal and Dynamic Systems

An introduction to linear systems and linear systems analysis. Topics include generalized effort and flow variables, bond graphs, first and second order systems, linear time-invariant discrete and continuous systems, Fourier series, Fourier transforms. Biological examples will be given of electrical, mechanical, hydrodynamic, thermal and chemical systems. Prerequisite: 171.102 Physics II. Corequisite: 110.302 Differential Equations.

Tung, Miller 4 credits

580.302 (E,S) Careers in Biomedical Engineering

See description for 580.202. This course is designed for upperclassmen who wish to meet with weekly speakers to discuss careers issues.

Popel 1 credit spring

580.311-312 (E,N) Design Team-Junior

A two semester course sequence where juniors and seniors work with a team leader and a group of BME freshmen and sophomores, to solve open-ended problems in biomedical engineering. Upperclassmen are expected to apply their general knowledge and experience, and their knowledge in their concentration area, to teach lower classmen and to generate the solution to practical problems encountered in biomedical engineering. Permission of course directors required.

Allen 3 credits per semester

580.402 (E) Neuroengineering

See description for 580.702.

Thakor 3 credits spring

580.411-412 (E,N) Design Team-Senior

Senior-level version of 580.311-312. Permission of course directors required.

Allen 3 credits per semester

580.413-414 (E,N) Design Team—Leader

A two-semester sequence where leaders direct a team of undergraduate biomedical engineering students in a series of design problems. Prior design team experience and permission of course directors required.

Allen 4 credits per semester

580.421 (E,N) Physiological Foundations I

A quantitative, model-oriented investigation of the cardiovascular system. Topics are organized in three segments. (1) Molecular/cellular physiology, including electrical signaling and muscle contraction. (2) Systems cardiovascular physiology, emphasizing circuit-diagram analysis of hemodynamics. (3) Cardiovascular horizons and challenges for biomedical engineers, including heart failure and its investigation/treatment by computer simulation, by gene-array analysis, by stem-cell technology, and by mechanical devices (left-ventricular assist and total-heart replacement). Prerequisites: 580.221 Molecules and Cells, 580.222 BME Signals and Systems, 110.302 Differential Equations. Corequisite: 580.423 Physiological Foundations Laboratory I.

Yue, Staff 4 credits

580.422 (E,N) Physiological Foundations for Biomedical Engineering II

A quantitative, model-oriented approach to the study of the nervous system. The course requires the use of simulations to explore dynamics of neural encoding of physiological signals. The first half of the course introduces functional anatomy of the central nervous system, models of neurons, neural networks, and learning and memory. The second half of the course introduces the structure and function of the auditory, visual and motor systems, with emphasis on the neural coding of sensory signals, adaptation of sensori-motor maps, and control of movements. Prerequisites: 580.221 Molecules and Cells, 580.222 BME Signals and Systems, 110.302 Differential Equations, 580.421 Physiological Foundations I. Corequisite: 580.424 Physiological Foundations Laboratory II.

Shadmehr, Staff 3 credits

580.423-424 Laboratory in Physiological Foundations for Biomedical Engineering I, II

A two-semester laboratory course in which various physiological preparations are used as examples of problems of applying technology in biological systems. The emphasis in this course is on the design of experimental measurements and on physical models of biological systems. Corequisites: 580.421-422.

Haase, Staff 2 credits

580.425 (E,N) Ionic Channels in Excitable Membranes

Ionic channels are key signaling molecules that support electrical communication throughout the body. As such, these channels are a central focus of biomedical engineering as it relates to neuroscience, computational biology, biophysics, and drug discovery. This course introduces the engineering (stochastic and mathematical models) and molecular strategies (cloning and expression) used to understand the function of ionic channels. The course also surveys key papers that paint the current picture of how channels open (gating) and conduct ions (permeation). Biological implications of these properties are emphasized throughout. Finally, the course introduces how optical (fluorescence methods) and electrophysiological methods (patch clamp) now promise to revolutionize understanding of ionic channels. This course can be viewed as a valuable partner of Models of Physiological Processes in the Neuron (580.439). Prerequisites: 580.421-422, or equivalent introductory biology. Recommended: differential equations, linear algebra, signals, and elementary probability.

Yue 3 credits spring/odd years

580.427 (E,N) Calcium Signals in Biological Systems

Calcium is a universal and versatile messenger that directly regulates diverse biological processes including muscle contraction, neurotransmission, and hormonal secretion. The course develops a quantitative treatment of mechanisms generating distinct calcium signals, and the transduction of such signals into biological responses. Examples will be drawn extensively from heart cells and neurons, as well as non-excitable cells. Topics include: experimental approaches to measuring intracellular calcium dynamics, physical basis and mathematical modeling of calcium dynamics and homeostasis, mechanism of decoding calcium signals and clinical implications of calcium dysregulation. Prerequisites: 580.421-422 or equivalent. Recommended: differential equations or signals and systems.

Colecraft 3 credits spring/even years

580.431 (E,N) Computational Motor Control

See description for 580.631.

Shadmehr 3 credits fall

580.435 (E,N) Bioelectromagnetic Phenomena

This course reviews theoretical concepts and experimental approaches used to characterize electric, magnetic, and electromagnetic phenomena that arise in biological tissues. Topics include the passive and active behavior of cell membranes, volume conductor models of cells and tissues, the bidomain model, bioelectric and biomagnetic measurements, electric and magnetic stimulation, and

impedance plethysmography and tomography. Prerequisites: 110.202, 110.302 (or 550.291), 520.213, 520.219, 520.214, 580.421 or equivalent.

Tung 3 credits fall/even years

580.439 (E,N) Models of Physiological Processes in the Neuron

Single-neuron modeling, emphasizing the use of computational models as links between the properties of neurons at several levels of detail. Topics include thermodynamics of ion flow in aqueous environments, biology and biophysics of ion channels, gating, nonlinear dynamics as a way of studying the collective properties of channels in a membrane, synaptic transmission, integration of electrical activity in multi-compartment dendritic tree models, and properties of neural networks. Students will study the properties of computational models of neurons; graduate students will develop a neuron model using data from the literature. Prerequisites: 580.421-422 or equivalent, 110.302 Differential Equations, or 500.303 Applied Mathematics I or equivalent. Recommended: 520.213 Circuits.

Young 4 credits fall

580.441 (E,N) Cellular Engineering

Lectures provide an overview of molecular biology fundamentals, an extensive review on extracellular matrix and basics of receptors, followed by topics on cell-cell and cell-matrix interactions at both the theoretical and experimental levels. Subsequent lectures will cover the effects of physical (shear, stress, strain), chemical (cytokines, growth factors), and electrical stimuli on cell function, emphasizing topics on gene regulation and signal transduction processes. Material on cell-cycle, apoptosis, metabolic engineering and gene therapy will also be incorporated into the course. Prerequisite: 580.221 Molecules and Cells.

Yarema 3 credits fall

580.442 (E,N) Tissue Engineering

Lectures provide an overview of tissue structure and function, followed by a review of biomaterials (collagen) and cell-biomaterial interactions. Subsequent lectures will cover fundamentals of stem cell biology, and discuss in depth, applications of tissue engineering to specialized tissues and organs, including skin; muscular skeletal system (bone, cartilage, tendon, and ligament); cardiovascular system (vascular grafts, blood substitutions, cardiac patch, and heart valve); nervous system (peripheral and central nervous systems); liver; pancreas, and kidney. Prerequisite: 580.421-422 Physiological Foundations I and II.

Elisseeff, Leong 3 credits spring

580.448 (E,N) Biomechanics of Cells and Organisms

Mechanical aspects of the cell are introduced using the concepts in continuum mechanics. We will discuss the role of proteins, membranes and cytoskeleton in cellular function and how to describe them using simple mathematical models. Prerequisites: 171.101-102, 110.108-109, 110.202. (Co-listed as 530.410)

Sun, Spector 3 credits spring

580.450 (E,N) Mechanics of Living Tissues

Review of continuum mechanics for large, finite deformations. Overview of constitutive properties of tissues, including viscoelasticity. Methods of mechanically testing tissues. The finite element method as applied to physiological problems. Mechanics of specific tissues and organs, e.g., heart, lung, bone. Prerequisites: 110.201 Linear Algebra, 560.206 Engineering Mechanics of Solids, 530.405 Mechanics of Solids and Structures, or equivalent.

Spector, Douglas 3 credits spring/even years

580.452 (E,N) Cellular and Tissue Engineering Laboratory

Cell and tissue engineering is a field that relies heavily on experimental techniques. This laboratory course will consist of six experiments that will provide students with valuable hands-on experience in cell and tissue engineering. Students will learn basic cell culture procedures and specialized techniques related to faculty expertise in cell engineering, microfluidics, gene therapy, microfabrication and cell encapsulation.

Haase 2 credits fall and spring

580.455 (E,N) Introduction to Orthopaedic Biomechanics

This course will cover static and dynamic forces in the musculoskeletal system, joint reactions, soft and hard tissue response to force loads, muscle mechanics, material properties, biomechanical lumped parameter systems, modeling and injury mechanisms. Prerequisites: 560.201 Statics, 110.302 Differential Equations.

Allen 3 credits spring/even years

580.460 (E,N) Physiological Fluid Mechanics

Basic concepts and problems of fluid and solid mechanics and rheology are introduced and applied to the analysis of blood flow in the macro- and microcirculation, and to other physiological flows. Analysis of mathematical models is combined with discussions of physiological mechanisms. Prerequisite: 110.302 Differential Equations.

Popel 3 credits spring/odd years

580.461 (E,N) Biological Transport

Basic principles and mechanisms of mass transport in multicomponent systems with application to biological phenomena. Examples of physiological mass and heat transfer. Mathematical models of pharmacokinetics and membrane transport. Students will carry out a modeling project of biological transport systems. Prerequisite: 110.302 Differential Equations.

Popel 3 credits fall/odd years

580.464 (E) Advanced Topics in Computer Vision

State-of-the-art methods in dynamic vision, with an emphasis on segmentation, reconstruction and recognition of static and dynamic scenes. Topics include: reconstruction of static scenes (tracking and correspondence, multiple view geometry, self calibration), reconstruction of dynamic scenes (2-D and 3-D motion segmentation, nonrigid motion analysis), recognition of visual dynamics (dynamic textures, face and hand gestures, human gaits, crowd motion analysis), as well as geometric and statistical

methods for clustering and unsupervised learning, such as K-means, Expectation Maximization, and Generalized Principal Component Analysis. Applications in robotics and biomedical imaging are also included. Prerequisites: 110, 202 and 600.461 or instructor's permission. (Co-listed as 600.462)

Vidal 3 credits spring

580.470 (E) Biomedical Instrumentation I: Molecular and Cellular

This core course will explore the fundamentals of molecular and cellular measurements, related technologies and their applications in scientific research. Fundamentals of molecules and cells, physical properties and micro and nanotechnologies will be reviewed first. This will be followed by basic principles of sensors, actuators, circuits and electronics. Finally, design and development of established as well as emerging technologies will be presented: electrophoresis, micro and nanotechnologies for DNA separation, microarray, DNA sequencing/synthesis, lab on a chip, fluorescence, confocal and two photon microscopy, atomic force microscopy and dip pen lithography. Course will include a guided lab. Prerequisite: 520.345.

Thakor 3 credits spring

580.471 (E) Principles of the Design of Biomedical Instrumentation II: Physiological and Clinical

This core design course will cover lectures and hands-on labs. The material covered will include fundamentals of biomedical sensors and instrumentation, FDA regulations, designing with electronics, biopotentials and ECG amplifier design, recording from heart, muscle, brain, etc., diagnostic and therapeutic devices (including pacemakers and defibrillators), applications in prosthetics and rehabilitation, and safety. The course includes extensive laboratory work involving circuits, electronics, sensor design and interface, and building complete biomedical instrumentation. The students will also carry out design challenge projects, individually or in teams (examples include "smart cane for blind," "computer interface for quadriplegic"). Prerequisite: 520.345.

Thakor 4 credits fall

580.472 (E) Medical Imaging Systems

An introduction to the physics, instrumentation, and signal processing methods used in general radiography, X-ray computed tomography, ultrasound imaging, magnetic resonance imaging, and nuclear medicine. The primary focus is on the methods required to reconstruct images within each modality, with emphasis on the resolution, contrast, and signal-to-noise ratio of the resulting images. Prerequisite: 520.214. (Co-listed as 520.432.)

Prince 3 credits spring

580.475 (E) Quantummechanical Basics of Nuclear Magnetic Resonance

Basics of NMR spectroscopy theory, data acquisition and processing. Topics include phenomenological/semi-classical description of NMR, introduction to quantum mechanics, quantum mechanics of NMR, density matrix, Cartesian spin operator formalism, homonuclear and heteronuclear pulse sequences for coupled spins, polariza-

tion transfer and coherence transfer, coherence transfer formalism, phase cycling for coherence selection, pulse sequences for multidimensional NMR, phase-sensitive and magnitude detection, and coherence selection using pulsed magnetic field gradients. Prerequisites: basic physics and mathematics.

Van Zijl, Pekar 3 credits fall/even years

580.482 (E,N) Computational Modeling of the Cardiac Myocyte

See description for 580.682.

Winslow 3 credits spring

580.495 Microfabrication Laboratory

This laboratory course introduces the principles used in the construction of microelectronic devices, sensors, and micromechanical structures. Students will work in the laboratory on the fabrication and testing of a device. Accompanying lecture material covers basic processing steps, design and analysis CAD tools, and national foundry services. Prerequisite: permission of instructor. (Co-listed as 520.495, 530.495.)

Andreou, J. Wang 4 credits fall

580.501-503 Freshman/Sophomore Research or Practicum in Biomedical Engineering

Research projects or engineering design projects under the supervision of any member of the BME faculty.

Staff up to 3 credits per term

580.511-513 Freshman/Sophomore Independent Study in Biomedical Engineering

Directed readings or other literature research under the direction of any member of the BME faculty.

Staff up to 3 credits per term

580.531-533 Junior/Senior Research or Practicum in Biomedical Engineering

Research projects or engineering design projects under the supervision of any member of the BME faculty. Prerequisite: junior or senior standing.

Staff up to 3 credits per term

580.541-543 Junior/Senior Independent Study in Biomedical Engineering

Directed readings or other literature research under the direction of any BME faculty member. Prerequisite: junior or senior standing.

Staff up to 3 credits per term

580.571 (E) Honors Instrumentation

Students enrolled jointly in 580.471 and 580.571 will not be required to take exams. Instead, students will develop a term paper and patent application and carry out a hands-on individual or team project throughout the semester and the intersession. Previous projects include design of EEG amplifier, voltage clamp and patch clamp, vision aid of blind, pacemaker/defibrillator, sleep detection and alert device, glucose sensor and regulation, temperature controller, eye movement detection and device control, ultrasound ranging and tissue properties, impedance plethysmogra-

phy, lie detector, blood alcohol detector, pulse oximeter, etc. Corequisite: must be enrolled in 580.471.

Thakor 2 credits intersession

580.580 (E) Biomedical Engineering Senior Design Project

Independent or team design project to design and evaluate a system. The design should demonstrate creative thinking and experimental skills, and must draw upon advanced topics of biomedical and traditional engineering. Project proposal and permission of the undergraduate program director are required.

Allen 3 credits

Graduate Courses

580.601-602 Seminar in Biomedical Engineering

Weekly seminar in which faculty, staff, graduate students, and outside speakers discuss topics of current research interest.

Staff 1 hour

580.603-604 Topics in Biomedical Engineering

A series of informal seminars in which faculty of the department discuss their research interests; emphasis is on discussion between faculty and students. The purpose is to introduce graduate students to research opportunities. Open to doctoral students in Biomedical Engineering; others by permission.

Colecraft 1 hour

580.610 Computational Functional Genomics

An introduction to mathematical and computational techniques for Functional Genomics, a growing area of research in cell biology and genetics whose objective is to understand the biological function of genes and their interactions. Computational functional genomics focuses on the problems of collecting, processing and analyzing data related to genome-wide patterns of gene expression with the objective to discover mechanisms by which a cell's gene expression is coordinated. This has become feasible with the development of DNA micro array technology, which allows the simultaneous measurement of gene expression levels of thousand of genes. Topics include: an introduction to cell biology (cells, genome, DNA, transcription, translation, control of gene expression, DNA and RNA manipulation), DNA microarray technology and experimental design, processing and analysis of micro array data (data reduction and filtering, clustering), and computational models for genetic regulatory networks (Boolean networks, Bayesian networks, ODE-based networks). Prerequisite: working knowledge of elementary probability and statistics. (Co-listed as 520.610)

Goutsias 2 hours spring

580.625-626 Structure and Function of the Auditory and Vestibular Systems

Physiological mechanisms of hearing and balance. Topics include transmission of sound in the ear, transduction of sound and head orientation by hair cells, biophysics and biochemistry of hair cells, representation of sound and

balance in eighth-nerve discharge patterns, anatomy of the central auditory and vestibular systems, and synaptic transmission and signal processing in central neurons. Aspects of hearing and balance such as speech perception, sound localization, vestibular reflexes and vestibular compensation are discussed with an integrated perspective covering perceptual, physiological, and mechanistic data. Prerequisites: 580.421-422 or equivalent. Recommended: 110.302 Differential Equations, 520.214 Signals and Systems.

Hearing Science Center Staff 3 hours
fall/even years, spring/odd years

580.628 Topics in Systems Neuroscience

This course consists of weekly discussions of current literature in systems neuroscience. The selected readings will focus on neural mechanisms for perception, attention, motor behavior, learning, and memory, as studied using physiological, psychophysical, computational, and imaging techniques. Students are expected to give presentations and participate in discussions. Prerequisite: 580.421-422 Physiological Foundations or equivalent.

X. Wang, Shadmehr 1 hour fall

580.629 Topics in System Neuroscience

This course consists of weekly discussions of current literature in systems neuroscience. The selected readings will focus on neural mechanisms for perception, attention, motor behavior, learning, and memory, as studied using physiological, psychophysical, computational, and imaging techniques. Students are expected to give presentations and participate in discussions. Prerequisite: 580.421-422 or equivalent.

X. Wang, Shadmehr 1 hour spring

580.630 Theoretical Neuroscience

Theoretical methods for analyzing information encoding and functional representations in neural systems. Models of single and multiple neural spike trains based on stochastic processes and information theory; detection and estimation of behaviorally relevant parameters from spike trains; system theoretic methods for analyzing sensory receptive fields; network models of neural systems. Both theoretical methods and the properties of specific well-studied neural systems will be discussed. Prerequisites: Introduction to Neuroscience (580.422 or equivalent), Probability (550.420 or equivalent), and Signals and Systems (520.214).

X. Wang, Young 2 hours spring/even year

580.631 Computational Motor Control

This course introduces tools from robotics, control theory, and computational neuroscience to understand in some depth the primate motor system. Our approach is to use mathematics to explore functions of muscles, spinal reflex systems, integration of vision and proprioception in the posterior parietal cortex, formation of motor plans, and on-line control. Our focus is on how various parts of the cortical and sub-cortical motor system contribute to the control and learning of movements, and how motor disorders arise from damage to these neural structures.

Prerequisites: 110.302 Differential Equations, 110.201 Linear Algebra.

Shadmehr 3 hours fall

580.632 Ionic Channels in Excitable Membranes

See 580.425 for description. Advanced homework problems, paper presentations, and exam questions are added to the core curriculum.

Yue 3 hours spring/odd years

580.633 Calcium Signals in Biological Systems

See 580.427 for description. Advanced homework problems, paper presentations, and exam questions are added to the core curriculum.

Colecraft 3 hours spring/even years

580.635 Project in Bioelectromagnetic Phenomena

See 580.435 for description. Paper presentations and advanced assignments are added to the core curriculum.

Tung 3 hours fall/even years

580.636 Feedback Control in Biological Signaling Pathways

Signal transduction pathways in biological systems need to be precisely regulated. This control is done through feedback regulatory loops. Students in this course will formulate mathematical models of signaling pathways and analyze their behavior using engineering control theory. Prerequisites: 110.302 Differential Equations, 520.353 Control Theory.

Iglesias 3 hours spring

580.639 Models of Physiological Processes in the Neuron

Graduate version of 580.439. Differs in that an advanced modeling project using data from the literature is required. Same prerequisites.

Young 4 hours fall

580.651 Introduction to Nonlinear Dynamics in Physiology

This course is designed for students who may be interested in applying the techniques of nonlinear dynamics and chaos to the analysis of physiological data. Topics covered will include fractals, strange attractors, bifurcations, state-space attractor reconstruction, Poincaré sections, dimension calculations, Lyapunov exponents, entropy, tests for determinism, nonlinear forecasting. Examples will be drawn from studies in cardiology, brain function, and the oculomotor system. Prerequisite: basic knowledge of signals and systems or permission of instructor.

Shelhamer 3 hours fall/even years

580.670 Biomedical Instrumentation II: Molecules and Cells

Graduate version of 580.470. Same prerequisites.

Thakor 3 hours spring

580.672 Biosensing and BioMEMS

The course discusses the principles of biosensing and introduces micro- and nano-scale devices for fluidic control and molecular/cellular manipulation, measurements

of biological phenomena, and clinical applications. (Co-listed as 530.672)

J. Wang 3 hours spring

580.682 Computational Models of the Myocyte

The cardiac myocyte is one of the most extensively studied cells in biology. As such, it serves as a critically important example of how to develop quantitative, dynamic computational models of cell function. The graduate-level course "Computational Models of the Cardiac Myocyte" will present a comprehensive review of all aspects of modeling of the cardiac myocyte. This includes a) experimental and theoretical approaches to the modeling of cardiac cell membrane ion channels and currents; b) models of voltage- and ion-dependent membrane transport systems, and cellular homeostatic mechanisms; c) intracellular calcium dynamics; d) force generation in cardiac myocytes; e) historical and modern integrative models of the cardiac myocyte; and f) models of disease processes in cardiac myocytes. The course will also cover emerging areas of modeling activity including a) mapping and modeling of signal transduction pathways in the cardiac myocyte; b) mechanisms by which such pathways modulate cell function. Prerequisites: Physiological Foundations of Biomedical Engineering or equivalent, differential equations or linear algebra/differential equations, and a semester-long college-level course in a programming language such as C, C++ or Fortran.

Winslow 3 credits spring

580.684 Experimental Foundations for Neural Models

This course familiarizes students with the experimental tools that are used to provide the biological data base for neural models. Projects are designed to teach single unit recording in sensory nerve; characterization of complex receptive fields; cellular or synaptic potential measurement; evoked potential techniques; psychophysical measurement of sensory or motor function. Prerequisites: an introductory course on the nervous system, permission of instructor.

Sachs, Staff 3 hours spring

580.687 Foundations of Computational Biology I

This course presents the fundamental concepts in equilibrium and non-equilibrium statistical mechanics and apply them to topics in modern molecular computational biology. Monte Carlo and statistical ensembles are presented. Field theories are introduced to describe the mechanics of membranes, cytoskeleton and biofluids. Kinetic theory, master equations and Fokker-Planck equations are discussed in the context of ion channels and molecular motors. (Co-listed with 530.687)

Sun 3 hours fall

580.688 Foundations of Computational Biology II

This course uses statistical mechanics and information theory to develop probabilistic models for biological data, with a primary focus on sequence data and graphical models. Topics will include probability theory, score matrices, hidden Markov models, suffix trees, phylogenetic inference, random graph theory, and network inference. Prerequisites: Mathematics through linear algebra

and differential equations; Molecular biology and genetics at the level of 580.221 or equivalent; 600.226 or equivalent. Homework assignments will require programming in a language of choice, and students will have access to a linux cluster as a computational resource. (co-listed with 530.688)

Bader 3 hours spring

580.690 Systems Biology of Cell Regulation

This course we will explore the recent advances in Systems Biology analysis of intracellular processes. Examples of the modeling and experimental studies of metabolic, genetic, signal transduction and cell cycle regulation networks will be studied in detail. The classes will alternate between consideration of network-driven and network element (gene, metabolite or protein)-driven approaches. Prerequisites: 110.201 and 110.302 or equivalent, advanced biology.

Levchenko 3 hours fall

580.691 Learning Theory

This course will be coverintroduce major ideas in computational learning, with an emphasis on its connections with biological learning. The focus is on the probabilistic foundations of learning theory. We will discuss topics in regression, Bayesian learning, classification, reinforcement learning, and active learning. However, this is not a machine learning course. Rather, our aim is to use mathematical results to model adaptation and formation of memory in the central nervous system, including problems in perception, sensori-motor adaptation, generalization, selection of action, consolidation, and addiction. Prerequisites: 550.291 or equivalent Linear algebra, probability theory. Prerequisites: 550.291 or equivalent.

Shadmehr, Diedrichsen 3 hours spring

580.702 Neuroengineering

Neuroengineering represents the application of engineering principles to develop systems for neurological research and clinical applications. This involves design of instrumentation for brain monitoring, development of signal processing methods to analyze brain rhythms, contemporary imaging methods ranging from optical/CT/MRI, use of micro and nanotechnologies to probe from neurons and brain, and development and application of neural stimulators, prosthesis, and deep brain stimulations and robotic/image guided therapeutic devices. The course will review and research the state of the art in selected fields and support research and development projects by students in these topics.

Thakor 3 hours

580.725 Medical Microsystems

Fundamental and advanced fabrication processes for integrating divers materials (including silicon) into micro-

structures and microdevices. Micropatterning, moulding, sensing, and actuation technologies. Research concepts and applications of microsystems at the molecular, cellular, and medical systems level. Applications such as DNA microarrays, drug and gene delivery, microsensors and actuators for research, microstructures for implants and microdevices for prostheses. Prerequisites: 580.471 or 580.495. Undergraduates by permission.

Andreas, Thakor 3 hours fall

580.744 Pattern Theory: From Representation to Inference

This course examines the metric pattern theory of Ulf Grenander in which shapes and patterns are studied as random processes on graphs. The course begins with the study of Markov processes on directed acyclic graphs, including Markov chains and branching processes, and on random fields on regular lattices. Moving to the continuum, the course examines Gaussian random fields, second order representation theory and random processes of geometric shape through Gaussian fields on manifolds. Numerous examples are examined in image understanding and image analysis.

Miller 3 hours spring

580.748 Magnetic Resonance in Medicine

(formerly 580.473)

This course provides the student with a complete introduction to the physical principles, hardware design, and signal processing used in magnetic resonance imaging and magnetic resonance spectroscopy. The course is designed for graduate students who wish to pursue research in magnetic resonance. Prerequisite: 520.214 Signals and Systems. Undergraduates by permission.

Atalar 3 hours spring/even year

580.801-802 Research in Biomedical Engineering

Staff credit varies

Cross-Listed

510.420 Topics in Biomaterials

Staff 3 credits

540.433 Engineering Aspects of Drug Delivery

Hanes 3 credits

600.439 Principles of Computational Biology

Staff 3 credits

600.445-446 Computer-Integrated Surgery I, II

Staff 3 credits

540.633 Engineering Aspects of Drug Delivery

Hanes 3 credits