BIOENGINEERING

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Courses given in Bioengineering have the subject code BIOE. For a complete list of subject codes, see Appendix.

The mission of the Department of Bioengineering is to create a fusion of engineering and the life sciences that promotes scientific discovery and the invention of new technologies and therapies through research and education. The department encompasses both the use of biology as a new engineering paradigm and the application of engineering principles to medical problems and biological systems. The discipline embraces biology as a new science base for engineering.

Bioengineering is jointly supported by the School of Engineering and the School of Medicine. The facilities and personnel of the Department of Bioengineering are housed in the James H. Clark Center, Allen Center for Integrated Systems, William F. Durand Building for Space Engineering and Science, William M. Keck Science Building, and the Richard M. Lucas Center for Magnetic Resonance Spectroscopy and Imaging.

The departmental headquarters is located in the James H. Clark Center for Biomedical Engineering and Sciences, along with approximately 600 faculty, staff, and students from more than 40 University departments. The Clark Center is also home to Stanford's Bio-X program, a collaboration of the Schools of Engineering, Medicine, Humanities and Sciences, and Earth Sciences.

Courses in the teaching program lead to the degrees of Master of Science and Doctor of Philosophy. The department collaborates in research and teaching programs with faculty members in Chemical Engineering, Mechanical Engineering, Electrical Engineering, and departments in the School of Medicine. Quantitative biology is the core science base of the department. The research and educational thrusts are in biomedical computation, biomedical imaging, biomedical devices, regenerative medicine, and cell/molecular engineering. The clinical dimension of the department includes cardiovascular medicine, neuroscience, orthopedics, cancer care, neurology, and environment.

UNDERGRADUATE PROGRAMS

Although primarily a graduate-level department, pre-approved B.S. majors in Biomechanical Engineering and Biomedical Computation can be arranged through the School of Engineering. For detailed information, see the "School of Engineering" section of this bulletin and the *Handbook for Undergraduate Engineering Programs* at http://ughb.stanford.edu and available from the Office of the Dean of Engineering.

COTERMINAL B.S./M.S. PROGRAM

This option is available to outstanding Stanford undergraduates who wish to work simultaneously toward a B.S. in another field and an M.S. in Bioengineering. The degrees may be granted simultaneously or at the conclusion of different quarters, though the bachelor's degree cannot be awarded after the master's degree has been granted. As Bioengineering does not currently offer an undergraduate program, the B.S. degree must be from another department. The University minimum requirements for the coterminal bachelor's/master's program are 180 units for the bachelor's degree plus 45 unduplicated units for the master's degree. Students may apply for the coterminal B.S. and M.S. program after 120 units are completed and they must be accepted into our program one quarter before receiving the B.S. degree. Students should apply directly to the Bioengineering Department. We require students interested in our coterminal degree to take the Graduate Record Examination (GRE); applications may be obtained at http://www.gre.org. New coterminal applications and procedures are now available on the Office of the University Registrar web site. Access the new application form, instructions, and supporting documents online at http://bioengineering.stanford.edu/education/coterminal.html; University regulations and forms concerning coterminal degree programs are available at http://registrar.stanford.edu/shared/publications.htm#Coterm.

The application must provide evidence of potential for strong academic performance as a graduate student. The application is evaluated and acted by the graduate admissions committee of the department. Students are expected to enter with a series of core competencies in mathematics, biology, chemistry, physics, computing, and engineering. Typically, a GPA of at least 3.5 in engineering, science, and math is expected.

GRADUATE PROGRAMS

The University's requirements for the M.S. and Ph.D. degrees are outlined in the "Graduate Degrees" section of this bulletin.

Admission—Students are expected to enter with a series of core competencies in mathematics, biology, chemistry, physics, computing, and engineering. Students entering the program are assessed by the examination of their undergraduate transcripts and research experiences. Specifically, we require that students have completed mathematics through multivariable calculus and differential equations, completed a series of undergraduate biology courses (equivalent to BIOSCI 41, 42, 43 series) and completed physics, chemistry, and computer sciences courses required of all undergraduate majors in engineering.

Qualified applicants are encouraged to apply for predoctoral national competitive fellowships, especially those from the National Science Foundation. Applicants to the Ph.D. program should consult with their financial aid officers for information and applications.

The deadline for receiving applications is January 2, 2007.

Further information and application forms for all graduate degree programs may be obtained from Graduate Admissions, the Registrar's Office, http://gradadmissions.stanford.edu/.

MASTER OF SCIENCE

The Master of Science in Bioengineering requires 45 units of course work. The curriculum consists of core bioengineering courses, technical electives, seminars and unrestricted electives. Core courses focus on quantitative biology and biological systems analysis. Approved technical electives are chosen by the student in consultation with his/her graduate adviser, and can be selected from graduate course offerings in mathematics, statistics, engineering, physical sciences, life sciences, and medicine. Seminars highlight emerging research in bioengineering and provide training in research ethics. Unrestricted electives can be freely chosen by the student in association with his/her adviser.

The department's requirements for the M.S. in Bioengineering are:

1. *Bioengineering courses* (12-13 units); the following courses are required:
   - BIOE 200A. Molecular and Cellular Engineering (Aut)
   - BIOE 200B. Systems Biology and Tissue Engineering (Win)
   - BIOE 200C. Medical Devices, Diagnostics, Pharmaceuticals (Spr)
   - BIOE 201A. Molecular and Cellular Engineering Lab (Aut)
   - BIOE 201C. Medical Devices, Diagnostics, Pharmaceuticals Lab (Spr)

   These courses, together with the approved technical electives, should form a cohesive course of study that provides depth and breadth.
2. *Approved Technical Electives* (24 units): these units must be selected from graduate courses in mathematics, statistics, engineering, physical science, life science, and medicine. They should be chosen in concert with the bioengineering courses to provide a cohesive degree program in a bioengineering focus area. Up to 9 units of directed study and research may be used as approved electives.

3. *Seminars* (3 units): the seminar units should be fulfilled through BIOE 390, Introduction to Bioengineering Research, BIOE 393, Bioengineering Forum, or BIOE 459, Frontiers in Interdisciplinary Biosciences. Other relevant seminar units may also be used with the approval of the faculty adviser. One of the seminar units must be MED 255, The Responsible Conduct of Research.
4. *Unrestricted Electives* (6 units).

Students are assigned an initial faculty adviser to assist them in designing a plan of study that creates a cohesive degree program with a concentration in a particular bioengineering focus area. These focus areas include, but are not limited to: Biomedical Computation, Regenerative Medicine/Tissue Engineering, Molecular and Cell Bioengineering, Biomedical Imaging, and Biomedical Devices.

To ensure that an appropriate program is pursued by all M.S. candidates, students who first matriculate at Stanford at the graduate level (a) submit an adviser approved "Program Proposal for a Master's Degree" form to the Student Service Office during the first month of the first quarter of enrollment and (b) obtain approval from the M.S. adviser and the Chair of Graduate Studies for any subsequent program change or changes. It is expected that the requirements for the M.S., Bioengineering can be completed within approximately one year. There is no thesis requirement for the M.S.

DOCTOR OF PHILOSOPHY

A student studying for the Ph.D. degree must complete a master's degree (45 units) comparable to that of the Stanford M.S. degree in Bioengineering. Up to 45 units of master's degree residency units may be counted towards the degree. The Ph.D degree is awarded after the completion of a minimum of 135 units of graduate work as well as satisfactory completion of any additional University requirements. Students admitted to the Ph.D. program with an M.S. degree must complete at least 90 units of work at Stanford. The maximum number of transfer units is 45.

Students are assigned an initial faculty adviser on the basis of the research interests expressed in their application. Initial faculty advisers assist students in selecting courses and identifying research opportunities. The department does not require formal lab rotations, but students are encouraged to explore research activities in two or three labs during their first academic year.

Prior to being formally admitted to candidacy for the Ph.D. degree, the student must demonstrate knowledge of bioengineering fundamentals and a potential for research by passing a qualifying oral examination.

Typically, the exam is taken shortly after the student earns a master's degree. The student is expected to have a nominal graduate Stanford GPA of 3.25 to be eligible for the exam. Once the student's faculty sponsor has agreed that the exam is to take place, the student must submit an application folder containing items including a curriculum vitae, research project abstract, and preliminary dissertation proposal to the student service office. Information about the exam may be obtained from the student service office.

In addition to the course requirements of the M.S. degree, doctoral candidates must complete a minimum of 15 additional units of approved formal course work (excluding research, directed study, and seminars).

Dissertation Reading Committee—Each Ph.D. candidate is required to establish a reading committee for the doctoral dissertation within six months after passing the department's Ph.D. Qualifying exams. Thereafter, the student should consult frequently with all members of the committee about the direction and progress of the dissertation research.

A dissertation reading committee consists of the principal dissertation adviser and at least two other readers. Reading committees in Bioengineering may include faculty from another department. It is expected that at least one member of the Bioengineering faculty be on each reading committee. The initial committee, and any subsequent changes, must be officially approved by the department Chair.

University Oral and Dissertation—The Ph.D. candidate is required to take the University oral examination after the dissertation is substantially completed (with the dissertation draft in writing), but before final approval. The examination consists of a public presentation of dissertation research, followed by substantive private questioning on the dissertation and related fields by the University oral committee (four selected faculty members, plus a chair from another department). Once the oral has been passed, the student finalizes the dissertation for reading committee review and final approval. Forms for the University oral scheduling and a one-page dissertation abstract should be submitted to the department student services office at least three weeks prior to the date of the oral for departmental review and approval.

M.D./PH.D. DUAL DEGREE PROGRAM

Students interested in a career oriented towards bioengineering and medicine can pursue the combined M.D./Ph.D. degree program. Stanford has two ways to do an M.D./Ph.D. U.S. citizens and permanent residents can apply to the Medical Scientist Training Program and can be accepted with funding from both M.D. and Ph.D. programs for stipend and tuition. They can then select a bioengineering laboratory for their Ph.D. Students not admitted to the Medical Scientist Training Program must apply to be admitted separately to the M.D. program and the Ph.D. program of their choice.

The Ph.D. is administered by the Department of Bioengineering. To be formally admitted as a Ph.D. degree candidate in this combined degree program, the student must apply through normal departmental channels and must have earned or have plans to earn an M.S. in bioengineering or other engineering discipline at Stanford or another university. The M.S. requires 45 units of course work which consists of core bioengineering courses, technical electives, seminars, and 6 unrestricted units. Students must also pass the Department of Bioengineering Ph.D. qualifying examination.

For students fulfilling the full M.D. requirements who earned their master's level engineering degree at Stanford, the Department of Bioengineering waives the normal departmental requirement of 15 units applied towards the Ph.D. degree beyond the master's degree level through formal course work. Consistent with the University Ph.D. requirements, the department accepts 15 units comprised of courses, research, or seminars approved by the student's academic adviser and the department chair. Students not completing their M.S. engineering degree at Stanford are required to take 15 units of formal course work in engineering-related areas as determined by their academic adviser.

COURSES

STANFORD INTRODUCTORY SEMINARS

BIOE 70Q. Medical Device Innovation—Stanford Introductory Seminar. Preference to sophomores. Commonly used medical devices in different medical specialties. Guest lecturers include Stanford Medical School physicians, entrepreneurs, and venture capitalists. How to identify clinical needs and design device solutions to address these needs. Fundamentals of starting a company. Field trips to local medical device companies; workshops. No previous engineering training required.

3 units, Spr (Doshi, Mandato)

ADVANCED UNDERGRADUATE AND GRADUATE

BIOE 191. Bioengineering Problems and Experimental Investigation—Directed study and research for undergraduates on a subject of mutual interest to student and instructor. Prerequisites: consent of instructor and adviser.

1-5 units, Aut, Win, Spr, Sum (Staff)

BIOE 200A. Molecular and Cellular Engineering—Preference to Bioengineering graduate students. The molecular and cellular bases of life from an engineering perspective. Quantitative analysis and engineering of biomolecules, molecular interactions, metabolism, signal transduction, and biophysical properties. Clinical motivations and biotechnology applications. Recommended: background in biochemistry.

3 units, Aut (Cochran, J)

BIOE 200B. Systems Biology and Tissue Engineering—Preference to Bioengineering graduate students. The interaction, communication, and disorders of organ systems. Major organ systems and engineering means of probing them. Relevant developmental biology and tissue engineering from cells to complex organs.

3 units, Win (Deisseroth, K)

BIOE 200C. Medical Devices, Diagnostics, and Pharmaceuticals—Preference to Bioengineering graduate students. Major classes of technologies including imaging techniques, chemical diagnostics, drug design and delivery. Topics include pacemakers, immunoassays, and biomaterials. Principles, practical limitations, and feature trade-offs in clinical settings.

3 units, Spr (Ku, J)

BIOE 201A. Molecular and Cellular Engineering Lab—Preference to Bioengineering graduate students. Practical studies of metabolism, information flow and feedback, signal transduction, and means for engineering these processes. Emphasis is on experimental design and data analysis. Corequisite: 200A.

1-2 units, Aut (Quake, S; Robinett, C)

BIOE 201C. Medical Devices, Diagnostics, and Pharmaceuticals Lab—Preference to Bioengineering graduate students. Medical devices and instrumentation for clinical diagnosis and drug development. Topics include medical devices, imaging systems (MRI, CT, ultrasound), and cardiovascular devices. Corequisite: 200C.

1-2 units, Spr (Pelc, N)

BIOE 220. Introduction to Imaging and Image-Based Human Anatomy—(Same as RAD 220.) The physics of medical imaging and human anatomy through medical images. Emphasis is on normal anatomy, contrast mechanisms, and the relative strengths of each imaging modality. Labs reinforce imaging techniques and anatomy. Recommended: basic biology, physics, and math.

3 units, Win (Gold, G; Butts Pauly, K)

BIOE 222A. Multimodality Molecular Imaging in Living Subjects I—(Same as RAD 222A.) Instruments for imaging molecular and cellular events using novel assays. Instrumentation physics, chemistry of molecular imaging probes, and applications to preclinical models and clinical disease management.

4 units, Aut (Gambhir, S; Rao, J)

BIOE 222B. Multimodality Molecular Imaging in Living Subjects—(Same as RAD 222B.) In vivo imaging techniques and applications to preclinical models and clinical disease management. Focus on cancer research, neurobiology, cardiovascular and musculoskeletal diseases.

4 units, Win (Gambhir, S; Rao, J)

BIOE 261. Principles and Practice of Stem Cell Engineering—(Same as NSUR 261.) Quantitative models used to characterize incorporation of new cells into existing tissues emphasizing pluripotent cells such as embryonic and neural stem cells. Molecular methods to control stem cell decisions to self-renew, differentiate, die, or become quiescent. Practical, industrial, and ethical aspects of stem cell technology application. Final projects: team-reviewed grants and business proposals.

3 units, Aut (Deisseroth, K; Palmer, T)

BIOE 281. Biomechanics of Movement—(Same as ME 281.) Experimental techniques to study human and animal movement including motion capture systems, EMG, force plates, medical imaging, and animation. The mechanical properties of muscle and tendon, and quantitative analysis of musculoskeletal geometry. Projects and demonstrations emphasize applications of mechanics in sports, orthopedics, and rehabilitation.

3 units, Aut (Delp, S)

BIOE 284A. Cardiovascular Bioengineering—(Same as ME 284A.) Bioengineering principles applied to the cardiovascular system. Anatomy of human cardiovascular system, comparative anatomy, and allometric scaling principles. Cardiovascular molecular and cell biology. Overview of continuum mechanics. Form and function of blood, blood vessels, and the heart from an engineering perspective. Normal, diseased, and engineered replacement tissues.

3 units, Aut (Taylor, C)

BIOE 284B. Cardiovascular Bioengineering—(Same as ME 284B.) Continuation of ME 284A. Integrative cardiovascular physiology, blood fluid mechanics, and transport in the microcirculation. Sensing, feedback, and control of the circulation. Overview of congenital and adult cardiovascular disease, diagnostic methods, and treatment strategies. Engineering principles to evaluate the performance of cardiovascular devices and the efficacy of treatment strategies.

3 units, Win (Taylor, C)

GRADUATE

BIOE 331. Protein Engineering—The design and engineering of optimized biomolecules emphasizing proteins. Combinatorial methodologies, protein structure and function, and biophysical analyses of modified biomolecules. Clinically relevant examples from the literature and industry. Prerequisite: basic biochemistry.

2-3 units, Win (Cochran, J)

BIOE 332A,B. Large-Scale Neural Modeling—Emphasis is on cortical computation, from feature maps in the neocortex to episodic memory in the hippocampus, and the roles of recurrent connectivity, rhythmic activity, spike synchrony, synaptic plasticity, and noise and heterogeneity. Techniques to predict and quantify network behavior applied to data recorded from models programmed and run in real-time on neuromorphic hardware developed for this purpose.

332A: *2 units, Win (Boahen, K)*
332B: *2 units, Spr (Boahen, K)*

BIOE 355. Advanced Biochemical Engineering—(Same as CHEMENG 355.) Approaches to combining new biological knowledge and methods with quantitative engineering principles for the production of beneficial products. Quantitative review of biochemistry and metabolism. Applications of recombinant DNA technology, synthetic biology, and metabolic engineering. The modern production of protein pharmaceuticals as a paradigm for advanced process development principles within the framework of current business and regulatory requirements. Prerequisite: CHEMENG 188 or BIOSCI 41, or equivalent.

3 units, Spr (Swartz, J)

BIOE 370. Microfluidic Device Laboratory—Fabrication of microfluidic devices for biological applications. Photolithography, soft lithography, and micromechanical valves and pumps. Emphasis is on device design, fabrication, and testing.

2 units, Win, Spr (Quake, S)

BIOE 374A. Biodesign Innovation: Needs Finding and Concept Creation—(Same as OIT 384, ME 374A, MED 272A.) Two quarter sequence. Strategies for interpreting clinical needs, researching literature, and searching patents. Clinical and scientific literature review, techniques of intellectual property analysis and feasibility, basic prototyping, and market assessment. Student entrepreneurial teams create, analyze, and screen medical technology ideas, and select projects for development.

3-4 units, Win (Yock, P; Makower, J; Zenios, S; Milroy, C)

BIOE 374B. Biodesign Innovation: Concept Development and Implementation—(Same as OIT 385, ME 374B, MED 272B.) Two quarter sequence. Concept development and implementation. Early factors for success; how to prototype inventions and refine intellectual property. Lectures, guest medical pioneers, and entrepreneurs about strategic planning, ethical considerations, new venture management, and financing and licensing strategies. Cash requirements; regulatory (FDA), reimbursement, clinical, and legal strategies, and business or research plans.

3-4 units, Spr (Yock, P; Makower, J; Zenios,S; Milroy, C)

BIOE 386. Neuromuscular Biomechanics—(Same as ME 386.) The interplay between mechanics and neural control of movement. State of the art assessment through a review of classic and recent journal articles. Emphasis is on the application of dynamics and control to the design of assistive technology for persons with movement disorders.
3 units, not given this year

BIOE 390. Introduction to Bioengineering Research—(Same as MED 289.) Preference to medical and bioengineering graduate students. Bioengineering is an interdisciplinary field that leverages the disciplines of biology, medicine, and engineering to understand living systems, and engineer biological systems and improve engineering designs and human and environmental health. Topics include: imaging; molecular, cell, and tissue engineering; biomechanics; biomedical computation; biochemical engineering; biosensors; and medical devices. Limited enrollment.
1-2 units, Aut, Win (Taylor, C)

BIOE 391. Directed Study—May be used to prepare for research during a later quarter in 392. Faculty sponsor required. May be repeated for credit.
1-6 units, Aut, Win, Spr, Sum (Staff)

BIOE 392. Directed Investigation—For Bioengineering graduate students. Previous work in 391 may be required for background; faculty sponsor required. May be repeated for credit.
1-10 units, Aut, Win, Spr, Sum (Staff)

BIOE 393. Bioengineering and Biodesign Forum—(Same as ME 389.) Guest speakers present research topics at the interfaces of biology, medicine, physics, and engineering. May be repeated for credit.
1 unit, Aut, Win, Spr (Staff)

BIOE 454. Synthetic Biology and Metabolic Engineering—(Same as CHEMENG 454.) Principles for the design and optimization of new biological systems. The development of new enzymes, metabolic pathways, and organisms for the production of central metabolites, amino acids, pharmaceutical proteins, polypeptide and polyketide antibiotics, and isoprenoids. Prerequisite: CHEMENG 250 or 355, or equivalent; 355 may be taken concurrently.
3 units, Spr (Swartz, J)

BIOE 459. Frontiers in Interdisciplinary Biosciences—(Same as BIOC 459, BIOSCI 459, CHEMENG 459, CHEM 459, PSYCH 459.) (Cross-listed in departments in the schools of H&S, Engineering, and Medicine; students register through their affiliated department; otherwise register for CHEMENG 459.) For specialists and non-specialists. Sponsored by the Stanford BioX Program. Three seminars per quarter address scientific and technical themes related to interdisciplinary approaches in bioengineering, medicine, and the chemical, physical, and biological sciences. Leading investigators from Stanford and the world present breakthroughs and endeavors that cut across core disciplines. Pre-seminars introduce basic concepts and background for non-experts. Registered students attend all pre-seminars; others welcome. See http://www.stanford.edu/group/biox/courses/459.html. Recommended: basic mathematics, biology, chemistry, and physics.
1 unit, Aut, Win, Spr (Robertson, C)

BIOE 484. Computational Methods in Cardiovascular Bioengineering—(Same as ME 484.) Lumped parameter, one-dimensional nonlinear and linear wave propagation, and three-dimensional modeling techniques applied to simulate blood flow in the cardiovascular system and evaluate the performance of cardiovascular devices. Construction of anatomic models and extraction of physiologic quantities from medical imaging data. Problems in blood flow within the context of disease research, device design, and surgical planning.
3 units, Spr (Taylor, C)

BIOE 485. Modeling and Simulation of Human Movement—(Same as ME 485.) Direct experience with the computational tools used to create simulations of human movement. Lecture/labs on animation of movement; kinematic models of joints; forward dynamic simulation; computational models of muscles, tendons, and ligaments; creation of models from medical images; control of dynamic simulations; collision detection and contact models. Prerequisite: 281, 331A,B, or equivalent.
3 units, not given this year

BIOE 500. Thesis (Ph.D.)
1-15 units, Aut, Win, Spr, Sum (Staff)

COGNATE COURSES

See respective department listings for course descriptions and General Education Requirements (GER) information. See degree requirements above or the program's student services office for applicability of these courses to a major or minor program.

BIOC 218. Computational Molecular Biology
3 units, Win (Brutlag, D)

BIOMEDIN 210. Introduction to Biomedical Informatics: Fundamental Methods—(Same as CS 270.)
3 units, Aut (Musen, M)

BIOMEDIN 212. Introduction to Biomedical Informatics Research Methodology—(Same as CS 272, GENE 212.)
3 units, Aut (Altman, R; Cheng, B; Klein, T)

BIOMEDIN 214. Representations and Algorithms for Computational Molecular Biology—(Same as CS 274, GENE 214.)
3-4 units, Spr (Altman, R)

EE 369A,B. Medical Imaging Systems
3 units, **A:** *Win,* **B:** *Spr (Nishimura, D)*

EE 369C. Medical Image Reconstruction
3 units, not given this year

ME 280. Skeletal Development and Evolution
3 units, Spr (Carter, D)

ME 381. Orthopaedic Bioengineering
3 units, Win (Carter, D)

ME 382A,B. Biomedical Device Design and Evaluation
4 units, **A:** *Win,* **B:** *Spr (Andriacchi, T)*

ME 385. Tissue Engineering Lab
1-2 units, Win (Jacobs, C)

RAD 226. In Vivo Magnetic Resonance Spectroscopy and Imaging
3 units, Win (Spielman, D)