UC San Diego
JACOBS SCHOOL OF ENGINEERING
Shu Chien-Gene Lay Department of Bioengineering

Bioengineering: Biosystems
Description of the Major

Introduction

Bioengineering/Biomedical Engineering (the terms are overwhelmingly used interchangeably) is perhaps the most rapidly expanding discipline in the USA and world-wide. Popularly it includes almost any mix of engineering and life sciences in any proportion to the point where most engineering programs embrace some form of bioengineering, but Bio/Biomedical engineering programs uniquely provide the depth at the intersection between life sciences and engineering expected for the 21st century workforce – industry, medicine, and research.

The UCSD Bioengineering Department has for decades been the national and international leader in bioengineering, establishing the Bioengineering Program, including an undergraduate degree in Bioengineering, in 1966. The department was formed in 1994.

To respond to the greatly expanding opportunities in bioengineering, the UCSD Bioengineering Department has created four distinct concentrations, each recognized as a separate undergraduate major, which makes it possible for us to offer highly focused and effective curricula to the advantage of our students.

The most recently added curriculum is that of Bioengineering: Biosystems.

Bioengineering: Biosystems

We agree that “Bioengineering: Biosystems” is a mouthful and that there is confusion, both because of the rapidly increasing popularity and impact of Systems Biology and Systems Medicine and the non-specific nature of “Systems Engineering”. We elaborate our rationale below:

First, a simplistic look at Systems Biology and Medicine shows the need for understanding and applying systems engineering. Biologists, especially at the molecular levels, have developed their science to the point where the measuring, modeling, designing and building of complex biological systems are not only possible scientifically but also of great value economically. Modeling of chemical reactions (often done with differential equations) has been extended to metabolic, protein, and DNA reactions; Synthetic Biologists are now designing genes and genetic circuits as well as customized metabolic and protein processes that are impacting medicine, agriculture and industry; and medicine today, de facto, underlies use of systems approaches for diagnostics, prognostics and therapeutics. Many of the tools used in these are those developed over the last century by electrical, mechanical and chemical engineers. Thus bio/biomedical engineering training has to incorporate systems engineering principles as applied to living systems – with the notion that we can attempt to study and characterize these living species and their function through systemic measurements, perturbations, quantitative modeling, temporal and dynamic analysis and analytical predictions. ,

The roots of “Systems Engineering” considerably predate our new major. Historically, what we now know as mechanical engineering began in the 1800’s to fill the need for practical training mostly with mechanics and devices; by the 1850’s chemical engineering came into being to deal with chemical processing and oil industries. Electrical engineering emerged in the early 1900’s with the rapidly electrification of the nation. Each became exceptionally sophisticated in the 20th century, including civil, industrial and agricultural engineering, disciplines driven not by fundamental science by application of the other engineering disciplines to very important spheres of activity. Computer science has rapidly evolved as computer technology has permeated all of modern society. Each area also developed its own mathematical methods: partial differential equations for mechanical engineering, transport phenomena and reactor kinetics for chemical engineering, and ordinary differential equations for electrical engineering.

In the 1960’s it became obvious that there was a need for an engineering discipline that focused on the connection or interaction between components and parts, and how integration and organization affects overall performance, rather than emphasizing individual characteristic domain problems. Systems Engineering has grown rapidly to become a significant part of most engineering departments; at some universities Systems Engineering is a stand-alone department. Wherever there are dynamic and interacting systems of phenomena and behavior, the mathematics and computer modeling of systems provide tremendous insight, whether the application is global warming or the stock market or supply chains. From the models spring designs which change the behavior of complex systems; nearly all highly engineered products are developed using systems engineering methodologies.

It should come as no surprise that medicine is rapidly discovering the power of systems engineering in almost all aspects of health care delivery – big data, epidemic outbreak modeling, personalized medicine, complex regulatory and insurance markets, and oversight of practitioner practice.

Hence, we believe that Biosystems Engineering is the next “big thing” in Bioengineering, whether it be molecular as in Systems and Synthetic Biology or global as in Healthcare.

The goal of Biosystems Engineering major is to enable students apply systems engineering to living systems. Engineering is playing an increasing role in physiology and medicine with applications ranging from molecular and cellular characterization of physiological and pathophysiological systems to engineering biomedical devices at scales from nano to macro to systems level measurements and analysis of whole physiology. Students who apply to Bioengineering undergraduate programs are increasingly in demand in biomedicine and hence need to be trained in the precepts of systems engineering. Our goal in this proposed major is to train students for i) a career in biomedical systems engineering, b) research and faculty positions in biosystems engineering with applications across a wide domain of physiology and medicine and c) further degrees in medicine and engineering. The quantitative training this Major offers will especially be highly suited for training the physicians of tomorrow. While we cannot provide you with the entire universe of opportunities within your four years of study, we can give you the basics of both life sciences – emphasizing both physiology and molecular biology – and systems engineering – emphasizing measuring, modeling, designing and predicting the future.

The basic principles of Systems Engineering involve:

Modeling and simulation
Optimization
Systems dynamics
Measurements and Systems Analysis
Statistical Analysis

In order to apply these principles to living systems, the curriculum needs to cover, components of living systems, which includes cellular and sub-cellular, tissue and physiological systems analysis; basic principles of interactions and properties of systems described by mechanical and electrical engineering.

Overview of the Curriculum

We break the curriculum down into these parts:

- preparation as a college graduate with a well-rounded education – your Humanities and Social Science Requirements
- preparation with mathematics and science needed for an Engineering undergraduate degree
- modern biology for engineers
- basic bioengineering coursework common to all bioengineers in the USA
- foci particular to the Biosystems major that enhance the preparation for a variety of careers
- senior design
- technical electives
- non-curricular opportunities

We elaborate on each below, followed by a year by year summary of the curriculum.

Well Rounded Education

At UCSD we have an exceptional and exceptionally strong system of academic and residential colleges. They provide scholarship, identity, camaraderie , etc. We are exceptionally proud that they step up and provide intellectual coherence to the breadth of your curriculum in the social sciences and humanities.

As a footnote we mention that all engineering programs must be accredited by ABET (Accreditation Board for Engineering and Technology) and that ABET demands that all engineering students have a solid liberal arts education. Your colleges exceed what ABET demands.

Never, ever, let someone claim that engineers are not well-rounded. You take more liberal arts courses than liberal arts majors take science and technology courses – and we are in an age where fluency in STEM (science, technology, math, engineering) is essential to being a fully engaged citizen.

Basic Engineering Preparation

There is no substitute for having a fundamental understanding of mathematics, physics, biology and chemistry. All engineers rely on this basic knowledge for their entire careers, long after they have forgotten the equations. These comprise the calculus (MATH 20ABCDE, 18), physics (PHYS 2ABC and sometimes D) and Chemistry (CHEM 6A, 6B and sometimes more) courses. While we agree less often on which computational courses should be required, it is clear that students, even in the liberal arts, should take as many CSE courses as their time and curriculum permit. Bioengineers are in a sense lucky in that biology is essential and built into the curriculum; some, but not nearly a majority, of universities require beginning biology of their engineering majors. With this solid science background, students are ready to pursue an engineering major.

Beginning Biology in an Engineering Context

Bioengineering students are faced with a daunting task – learning enough basic biology at enough scales – in a very short period of time during their second and third years. For Biosystems (and other) majors we most strongly emphasize Physiology (BENG 140A/B), a two quarter sequence that introduces all the major physiological systems. Students emerge with a new vocabulary – they can now discuss most human diseases with accuracy – as well as see how both research and the practice of medicine are organized. Secondly, we introduce molecular biology (BENG 102), the science that has recently revolutionized all of biology and medicine. Similarly, with their vocabulary and understanding greatly widened, students are ready for upper level courses, work in research labs and even in many summer internships.

Students also take a bioengineering version of Organic Chemistry – both fundamental for BioE and ChemE students but foreign for other engineers.

We add that the Bioengineering Department teaches these fundamental courses in an “engineering aware” manner – more modeling, more measurements, more computation, more systems thinking. There is a difference between the quantitation that a bioengineer encounters and the qualitative understanding of the life scientist.

Engineering in a Bioengineering Context

All our bioengineers need more experience applying engineering approaches to biomedical problems. While time is short, they learn about biomechanics (BENG 110), the modeling of chemical and other kinetics (BENG 103B), biomedical instrumentation (BENG 186B) and biomedical and biological imaging (BENG 141). In senior year they take an advanced biocomputation/modeling course (BENG 125). They emerge with a solid understanding of many of the approaches used by other disciplines but with particular knowledge of the advantages and limitations of application to the biomedical field.

Uniquely Biosystems

We expect our students to be especially strong in the modeling of biomedical systems. This is already an enormous application area and one that will continue to expand rapidly because of the confluence of the two most rapidly developing technologies on earth, which happen to be the foci of our Biosystems major: systems biology (molecular to physiological) and computational/modeling science. Students in Biosystems are solidly grounded in molecular biology and physiology and then learn much more about computation (BENG 133 Numerical Techniques), signals and modeling (BENG 125 Biocomputational Modeling; BENG 122A Biocontrols; BENG 135 Biosignals; BENG 189 capstone physiological modeling). The overlap of BENG 152 (Lab, instrumentation, physiological signal transduction) and BENG 186B gives students great insight into the revolution in sensing, especially as applied to individuals and expressed as wireless biomedical technology. Students are thoroughly grounded in statistical and probabilistic modeling (including some data mining) through (BENG 133, 134, 135). In all our students are well-grounded in the fundamentals of Systems Engineering: modeling and simulation; optimization; systems dynamics; measurements and systems analysis; and statistical analysis.

Senior Design for All Bioengineering Majors

The UCSD Bioengineering Senior Design course sequence has the philosophy of "Capstone" design courses, where students use a variety of their previously learned skills to solve a focused engineering problem. The course also serves to meet additional ABET Outcomes and Learning Objectives, including formal design and decision making processes, working in teams, and awareness of ethical and societal consequences.

This course sequence includes two components: BENG 187A/B/C/D, each a 1 credit hour lecture course, taken in the student's last four quarters (Spring/Fall/Winter/Spring); and two 3 credit hour project courses taken in Fall and Winter quarters. The goal of the entire experience is for students to gain experience with a formal design and reporting process, mostly through BENG 187, and to have hands-on experience with engineering design and implementation for biomedical applications through their project courses. They also gain brief introductions to FDA, animal and human subjects, ethics, and presentation skills.

Technical Electives for BioSystems Engineers

Biosystems majors must take 8 units of technical elective courses, all of which have engineering content in order to satisfy accreditation requirements. These must be taken for a letter grade, be of upper division level, not required for the major and in the Jacobs School of Engineering. While BENG 199 Independent Study courses are highly encouraged in general, there are restrictions. Please discuss with UG Advising Staff or faculty.

Curriculum Beyond the Curriculum

A great many Bioengineering students, including Biosystems majors, have very greatly enriched their education with experiences outside the classroom and outside the curriculum.

One of the greatest opportunities afforded by universities over the entire USA is the great range of opportunities beyond the classroom. Three simple looks illustrate tremendous sources of opportunities for UCSD Biosystems majors: (a) Bioengineering and related health sciences research opportunities on campus; (b) the Biotech corridor along North Torrey Pines Road; (c) the "mega" industrial complex which is San Diego.

Suggestions include:

BENG 191 – Senior Seminar in Bioengineering – please come! Do not worry about understanding most of the lecture – you should go with the goal of finding out why the lecturer is excited about what s/he does. There are lots of seminars in Bioengineering, other engineering departments and the medical school. Do not be intimidated.

Research Experiences – a large fraction of our students find opportunities in faculty research labs; many are Bioengineering faculty, but there are also many opportunities in other departments, the UCSD School of Medicine, the Scripps Oceanographic Institute or the Salk Institute. These are enormously valuable.

Other on-campus experiences – some of our students find exceptional experiences in engineering project teams, including Global Ties and Engineering World Health.

Student professional societies provide exceptional opportunities for leadership experience and enhancements to your education. Please check out the BioMedical Engineering Society (BMES), the Engineering in Medicine and Biology Society (EMBS), the International Society for Pharmaceutical Engineering, SynBio, and the Undergraduate Bioinformatics Club.

Internships: many students have found summer jobs or internships which greatly augment their intellectual development. Please contact our internship office for help

Getting a great “beyond the curriculum” experience is part of why you pay tuition. But you have to hustle to take advantage.

Year by Year Summary of the Bioengineering: Biosystems Major
(Abbreviated course titles are used. Most courses: 4 units of credit. 1* unit and 2** unit courses are marked.)

First Year
This year is dominated by traditional STEM courses that provide the intellectual ground work for all engineering majors: two terms of calculus (MATH 20A,20B); two terms of Physics (mechanics and electricity and magnetism PHYS 2A,2B, 2BL (lab)); and chemistry (CHEM 6A, 6B). Math 18 (linear algebra) is a prerequisite for the sophomore circuits class (ECE 35). The Biosystems majors take an introductory Matlab programming course (BENG 2) giving students sufficient programming knowledge to use computation in their other UG courses. Finally BENG 1 gives students a hands on experience with bioengineering projects. Students also take Humanities and Social Science Courses that are required of all engineering majors, but customized to the requirements of their residential college.

Fall First Year
Humanities/Social Sciences
MATH 20A Calculus for Engrs I
CHEM 6A General Chemistry I
BENG 2* Intro Program Matlab

Winter First Year
Humanities/Social Sciences
MATH 20B Calculus for Engrs II
CHEM 6B General Chemistry II
PHYS 2A Physics Mechanics
BENG 1** Intro Bioengineering

Spring First Year
Humanities/Social Sciences
MATH 20C Calculus/Analytic Geometry
PHYS 2B / 2L** Electricity and Magnetism with Lab
ECE 35 Electrical Circuits

Second Year
This year begins with the completion of foundational engineering courses and the transition to beginning and foundational Bioengineering courses. The math sequence finishes with differential equations (MATH 20D, foundational to dynamic modeling of biosystems), vector calculus (MATH 20E, foundational biophysical modeling) and linear algebra (MATH 18, foundational for signal processing and high dimensional data). PHYS 2C (Fluids, waves, thermodynamics, optics) presages Bioengineering courses in multiple areas. Special to the Systems majors is ECE 35 (Intro to Analog Design, which is mostly equivalent to the beginning electrical circuits course taken by most engineering majors world wide; see also the discussion of the circuits track importance for Biosystems majors. Biosystems majors also take ECE 45 (Circuits and Systems) which provides their first exposure to the mathematics of systems, and find this reinforced in BENG 100 (Statistical Reasoning) which provides the basis for a wide range of applications from probabilistic modeling to statistical evaluation of testing data. Fundamentals of biological/bioengineering systems appear in BENG 120 (Organic Chemistry, taught from an engineering perspective) and BENG 102 (Molecular Components of Living Systems); these two courses emphasize fundamentals underlying current spectacular advances in molecular biology. Again, students also take Humanities and Social Science Courses that are required of all engineering majors, but customized to the requirements of their residential college.

Fall Second Year
Humanities/Social Sciences
MATH 20D Differential Equations
Phys 2C / 2L** Fluids, Waves, Optics, Thermo; with Lab
ECE 45 Circuits & Systems

Winter Second Year
Humanities/Social Sciences
Humanities/Social Sciences
MATH 20E Vector Calculus
BENG 120 Organic Chemistry

Spring Second Year
Humanities/Social Sciences
MATH 18 Linear Algebra
BENG 102 Molecular Biology
BENG 100 Probability & Statistics

Third Year

This year very strongly emphasizes bioengineering courses that expand from fundamental mathematical and biological foundations to applications found throughout the bioengineering and Biosystems work and research world. Most central for biomedical engineers is the BENG 140A/B sequence in physiology – at its simplest, this is what all parents need to know when their child is sick; at heart, however, is basic understanding of the body and how medical practitioners think about the biological basis of most of their profession. Supporting are the following courses: BENG 110 – how to think about the body as a mechanical system; BENG141 – the use of imaging technologies to discover biomedicine from cells to whole bodies; BENG 130 -- the role of heat and kinetics in biological systems. Biosystems majors increase their competency is experimental and modeling basics and technology with the instrumentation pair (BENG 152 Laboratory dedicated to implementing biosignal acquisition and analysis for Biosystems majors; and BENG 186B Bioinstrumentation lecture course) that dominate physiological biomedical engineering. Biosystems majors also learn in depth about the computational and statistical understanding critical to systems modeling and thinking while taking BENG 133 (Numerical Analysis/Computational Thinking) and BENG 134 (advanced measurements/statistics/probability).
Again, students take Humanities and Social Science Courses that are required of all engineering majors, but customized to the requirements of their residential college. They also begin the senior design sequence described below.

Fall Third Year
Humanities/Social Sciences
BENG 134 Adv Prob/Stat
BENG 141 Biomed Imaging
BENG 110 Continuum Mechanics

Winter Third Year
BENG 140A Physiology I
BENG 130 BioThermo/Kinetics
BENG 186B BioInstr. Lecture
BENG 152 Bioinst/Sys Lab

Spring Third Year
Humanities/Social Sciences
BENG 140B Physiology II
BENG 133 Numerical Techniques
BENG 187A* Senior Design

Fourth Year

Senior year for Biosystems majors is dominated by capstone courses. These include the classical Senior Design sequence described elsewhere, but also a Computational Bioengineering course (BENG 125) and a Physiological Systems Modeling course (BENG 189) that bring together the students' diverse biological knowledge and their mathematical/computational skills.
Again, students take Humanities and Social Science Courses that are required of all engineering majors, but customized to the requirements of their residential college.

Fall Fourth Year
BENG 122A Biocontrol
BENG 135 Bio Signals
BENG 187B and BENG 1XXA Senior Design
BENG Technical Elective

Winter Fourth Year
Humanities/Social Sciences
Humanities/Social Sciences
BENG 187C and BENG 1XXB Senior Design
BENG Technical Elective

Spring Fourth Year
Humanities/Social Sciences
BENG 125 Computational Bioengineering
BENG 189 Physiological Systems Engineering
BENG 187D* Senior Design

Note: Humanities/Social Science and Technical Elective courses should be scheduled so as to balance workload and course offerings.