ENGINEERING & APPLIED SCIENCE

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M.S., M.Phil., Ph.D.

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Associate Professors Stuart Campbell, Michael Choma, Tarek Fahmy, Rong Fan, Anjelica Gonzalez, Themis Kyriakides (Pathology), Chi Liu, Kathryn Miller-Jensen, Jiangbing Zhou

Assistant Professors Michael Mak, Michael Murrell

CHEMICAL & ENVIRONMENTAL ENGINEERING
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Associate Professor John Fortner

Assistant Professors Drew Gentner, Amir Haji-Akbari, Shu Hu, Mingjiang Zhong

Lecturers Aniko Bezur, Paul Whitmore

COMPUTER SCIENCE
Chair
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Associate Professors Mahesh Balakrishnan, Abhishek Bhattacharjee, Sahand Negahban*

Assistant Professors Yang Cai, Wenjun Hu,* Julian Jara-Ettinger, Amin Karbasi,* Smita Krishnaswamy,* Ruzica Piskac, Mariana Raykova, Jakub Szefer,* Marynel Vázquez

Senior Lecturer Stephen Slade

Lecturers Benedict Brown, James Glenn, Kyle Jensen,* Scott Petersen, Brad Rosen, Andrew Sherman, Xiyin Tang [Sp]
A secondary appointment with primary affiliation in another department or school.
A joint appointment with another department.

**ELECTRICAL ENGINEERING**

**Chair**
Leandros Tassiulas

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**Professors** James Duncan, Jung Han, Roman Kuc, Tso-Ping Ma, Rajit Manohar, A. Stephen Morse, Kumpati Narendra, Daniel Prober, Mark Reed, Peter Schultheiss (Emeritus), Lawrence Staib, Hong Tang, Leandros Tassiulas, J. Rimas Vaisnys, Y. Richard Yang

**Associate Professors** Richard Lethin (Adjunct), Sekhar Tatikonda, Fengnian Xia

**Assistant Professors** Wenjun Hu, Amin Karbasi, Jakub Szefer

**MECHANICAL ENGINEERING & MATERIALS SCIENCE**

**Chair**
Udo Schwarz

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Jan Schroers (jan.schroers@yale.edu)

**Professors** Charles Ahn, Ira Bernstein (Emeritus), Juan Fernández de la Mora, Aaron Dollar, Alessandro Gomez, Sohrab Ismail-Beigi, Shun-Ichiro Karato, Marshall Long, Corey O’Herne, Brian Scassellati, Jan Schroers, Udo Schwarz, Mitchell Smooke

**Associate Professor** Judy Cha

**Assistant Professors** Eric Brown, Rebecca Kramer-Bottiglio, Madhusudhan Venkadesan

**Lecturers** Beth Anne Bennett, Joran Booth, Kailasnath Purushothaman, Joseph Zinter

Programs of study are offered in the areas of applied mechanics, computer science, mechanical engineering and materials science, chemical and environmental engineering, electrical engineering, and biomedical engineering. All programs are under the School of Engineering & Applied Science.

**BIOMEDICAL ENGINEERING**

**Fields of Study**

Biological and medical devices, biological signals and sensors, biomaterials, biomechanics, biophotonics, computational medicine, computer vision, digital image analysis and processing, drug delivery, energy metabolism, gene therapy, modeling in mechanobiology, MRI, MRS, PET and tracer kinetic modeling, nanomedicine, network analysis, the physics of image formation (MRI, optics, ultrasound, nuclear medicine, and X-ray), physiology and human factors engineering, signaling pathways, systems biology, systems medicine, tissue engineering and regenerative medicine, and vascular biology.

**CHEMICAL & ENVIRONMENTAL ENGINEERING**

**Fields of Study**

Fields include nanomaterials, soft matter, interfacial phenomena, energy, water and air quality, and sustainability.

**COMPUTER SCIENCE**

**Fields of Study**

Algorithms and computational complexity, artificial intelligence, data networking, databases, graphics, machine learning, programming languages, robotics, scientific computing, security and privacy, and systems.

**ELECTRICAL ENGINEERING**

**Fields of Study**

Fields include biomedical sensory systems, communications and signal processing, neural networks, control systems, wireless networks, sensor networks, microelectromechanical and nanomechanical systems (MEMS and NEMS), nanoelectronic science and technology, optoelectronic materials and devices, semiconductor materials and devices, quantum and nonlinear photonics, quantum materials and engineering, computer engineering, computer architecture, hardware security, and VLSI design and testing.
MECHANICAL ENGINEERING & MATERIALS SCIENCE

Fields of Study

**Fluids and thermal sciences** Suspensions; electrospray theory and characterization; electrical propulsion applications; electrified and magnetized interfaces of electrically conducting liquids and ferrofluids; combustion and flames; computational methods for fluid dynamics and reacting flows; turbulence; laser diagnostics of reacting and nonreacting flows; and magnetohydrodynamics.

**Soft matter/complex fluids** Jamming and slow dynamics in gels, glasses, and granular materials; mechanical properties of soft and biological materials; and structure and dynamics of proteins and other macromolecules. Several faculty in Mechanical Engineering are also affiliated with the Integrated Graduate Program in Physical and Engineering Biology (http://peb.yale.edu).

**Materials science** Studies of thin films; nanoscale effects on electronic properties of two-dimensional layered materials; amorphous metals and nanomaterials including nanocomposites, characterization of crystallization and other phase transformations; nanoimprinting; atomic-scale investigations of surface interactions and properties; classical and quantum nanomechanics; nanotribology; nanostructured energy applications; nanoparticle synthesis for energy applications; combinatorial materials science; and in situ transmission electron and scanning probe microscopy.

**Robotics/mechatronics** Machine and mechanism design; dynamics and control; robotic grasping and manipulation; human-machine interface; rehabilitation robotics; haptics; soft robotics; flexible and stretchable electronics; soft material manufacturing; responsive material actuators; soft-bodied control; electromechanical energy conversion; biomechanics of human movement; mechanics of biological muscle; and human-powered vehicles.

**INTEGRATED GRADUATE PROGRAM IN PHYSICAL AND ENGINEERING BIOLOGY (PEB)**

Students applying to the Ph.D. program in Biomedical Engineering, Chemical & Environmental Engineering, and Mechanical Engineering & Materials Science may also apply to be part of the PEB program. See the description under Non-Degree-Granting Programs, Councils, and Research Institutes for course requirements, and http://peb.yale.edu for more information about the benefits of this program and application instructions.

**SPECIAL ADMISSIONS REQUIREMENT**

The General Test of the GRE is required for all programs in the School of Engineering & Applied Science.

**SPECIAL REQUIREMENTS FOR THE PH.D. DEGREE**

The online publication *Qualification Procedure for the Ph.D. Degree in Engineering & Applied Science* describes in detail all requirements in Biomedical Engineering, Chemical & Environmental Engineering, Electrical Engineering, and Mechanical Engineering & Materials Science. The student is strongly encouraged to read it carefully; key requirements are briefly summarized below. See Computer Science’s departmental entry in this bulletin for special requirements for the Ph.D. in Computer Science.

Students plan their course of study in consultation with faculty advisers (the student’s advisory committee). A minimum of ten term courses is required, to be completed in the first two years. Well-prepared students may petition for course waivers based on courses taken in a previous graduate degree program. Similarly, students may place out of certain ENAS courses via an examination prepared by the course instructor. Placing out of the course will not reduce the total number of required courses. Core courses, as identified by each department/program, should be taken in the first year unless otherwise noted by the department. With the permission of the departmental director of graduate studies (DGS), students may substitute more advanced courses that cover the same topics. No more than two courses can be Special Investigations, and at least two must be outside the area of the dissertation. All students must complete a one-term course, Responsible Conduct of Research, in the first year of study.

Each term, the faculty review the overall performance of the student and report their findings to the DGS who, in consultation with the associate dean, determines whether the student may continue toward the Ph.D. degree. By the end of the second term, it is expected that a faculty member has agreed to accept the student as a research assistant. By December 5 of the third year, an area examination must be passed and a written prospectus submitted before dissertation research is begun. These events result in the student’s admission to candidacy. Subsequently, the student will report orally each year to the full advisory committee on progress. When the research is nearing completion, but before the thesis writing has commenced, the full advisory committee will advise the student on the thesis plan. A final oral presentation of the dissertation research is required to be given during term time. There is no foreign language requirement.

Teaching experience is regarded as an integral part of the graduate training program at Yale University, and all Engineering graduate students are required to serve as a Teaching Fellow for one term, typically during year two. Teaching duties normally involve assisting in laboratories or discussion sections and grading papers and are not expected to require more than ten hours per week. Students are not permitted to teach during the first year of study.

If a student was admitted to the program having earned a score of less than 26 on the Speaking Section of the Internet-based TOEFL, the student will be required to take an English as a Second Language (ESL) course each semester at Yale until the Graduate School’s Oral English Proficiency standard has been met. This must be achieved by the end of the third year in order for the student to remain in good standing.
CORE COURSE REQUIREMENTS FOR THE PH.D. DEGREE

Biomedical Engineering  Physiological Systems (ENAS 590), Physical and Chemical Basis of Bioimaging and Biosensing (ENAS 510). One of these courses may be taken in the second year. In addition, there is a math requirement that must be met by taking Biomedical Data Analysis (ENAS 549), Mathematical Methods I (ENAS 500), or Advanced Engineering Mathematics (ENAS 505) in the first year.

Chemical & Environmental Engineering (Chemical track)  Mathematical Methods I (ENAS 500), Classical and Statistical Thermodynamics (ENAS 521), Energy, Mass, and Momentum Processes (ENAS 603), Chemical Reaction Engineering (ENAS 602).

Chemical & Environmental Engineering (Environmental track)  Biological Processes in Environmental Engineering (ENAS 641), Environmental Physicochemical Processes (ENAS 642), and either Water Chemistry (ENAS 638) or Aquatic Chemistry (ENAS 640). In addition, there is a math requirement that must be met by taking one of the following courses in the first year: Mathematical Methods I (ENAS 500), Applied Spatial Statistics (F&ES 781), Multivariate Data Analysis in the Environmental Sciences (F&ES 758), Data Exploration and Analysis (S&DS 530), or Multivariate Statistical Methods for the Social Sciences (S&DS 563).

Computer Science  See the departmental entry for Computer Science in this bulletin.

Electrical Engineering (Computer Engineering track)  Competence must be demonstrated in at least two of the three research areas. At least two courses that cover two different areas are required. In the area of computer organization and architecture, the course options are Computer Architectures and Artificial Intelligence (ENAS 907) and Computer Organization and Architecture (ENAS 967). In the area of VLSI, the course options are Introduction to VLSI System Design (ENAS 875) and Silicon Compilation (ENAS 876). In the area of computer systems, the course options are Principles of Operating Systems (CPSC 523), Building Distributed Systems (CPSC 526), Computer Networks (CPSC 533), Topics on the Hardware/Software Interface (CPSC 635), and Cloud FPGA (ENAS 968).

Electrical Engineering (Microelectronics track)  Two of the following four courses: Physics and Devices of Optical Communication (ENAS 411), Heterojunction Devices (ENAS 718), Solid State Physics I (ENAS 850), Semiconductor Silicon Devices and Technology (ENAS 986).

Electrical Engineering (System and Signals track)  Linear Systems (ENAS 902), Stochastic Processes (ENAS 502).

Mechanical Engineering & Materials Science  Students must demonstrate competence in one of four areas: Fluid and Thermal Sciences, Soft Matter/Complex Fluids, Materials Science, or Robotics/Mechatronics. As a minimum requirement, students must take at least one of the following courses in the first year of study: Intelligent Robotics (CPSC 572), Intelligent Robotics Laboratory (CPSC 573), Classical and Statistical Thermodynamics (ENAS 521), Biological Physics (ENAS 541), Polymer Physics (ENAS 606), Synthesis of Nanomaterials (ENAS 615), Statistical Physics II (PHYS 628), Introduction to Nanomaterials and Nanotechnology (ENAS 703), Theoretical Fluid Dynamics (ENAS 704), Fundamentals of Combustion (ENAS 708), Solidification and Phase Transformations (ENAS 752), Introduction to Robot Analysis (ENAS 777), Forces on the Nanoscale (ENAS 787), Soft Condensed Matter Physics (ENAS 848), Solid State Physics I (ENAS 850), Solid State Physics II (ENAS 851), Linear Systems (ENAS 902; if not used to satisfy the math requirement), Systems and Control (ENAS 936), and Mechatronics Laboratory (ENAS 994). In addition, there is a math requirement that must be met by taking Mathematical Methods I (ENAS 500), Mathematical Methods of Physics (PHYS 506), or Linear Systems (ENAS 902), depending on the research area.

HONORS REQUIREMENT

Students must meet the Honors requirement in at least two term courses (excluding Special Investigations) by the end of the second term of full-time study. An extension of one term may be granted at the discretion of the DGS. An average grade of at least High Pass must be maintained through all courses that count toward the Ph.D.

MASTER’S DEGREES

M.Phil.  See Degree Requirements under Policies and Regulations.

M.S. (en route to the Ph.D.)  To qualify for the M.S., the student must pass eight term courses; no more than two may be Special Investigations. An average grade of at least High Pass is required, with at least one grade of Honors.

Terminal Master’s Degree Program  Students may also be admitted directly to a terminal master’s degree program. The requirements are the same as for the M.S. en route to the Ph.D., although there are no core course requirements for students in this program. This program is normally completed in one year, but a part-time program may be spread over as many as four years. Some courses are available in the evening, to suit the needs of students from local industry.

Program materials are available upon request to the Office of Graduate Studies, School of Engineering & Applied Science, Yale University, PO Box 208292, New Haven CT 06520-8292; e-mail, engineering@yale.edu; website, http://seas.yale.edu.

COURSES

The list of courses may be slightly modified by the time term begins. Please visit https://courses.yale.edu for the most updated course listing.
ENAS 500b, Mathematical Methods 1  J. Rimas Vaišnys
A beginning, graduate-level introduction to ordinary and partial differential equations, vector analysis, linear algebra, and complex functions. Laplace transform, series expansion, Fourier transform, and matrix methods are given particular attention. Applications to problems frequently encountered in engineering practice are stressed throughout.

ENAS 502b, Stochastic Processes  Amin Karbasi
Introduction to the study of random processes, including Markov chains, Markov random fields, martingales, random walks, Brownian motion, and diffusions. Techniques in probability such as coupling and large deviations. Applications chosen from image reconstruction, Bayesian statistics, finance, probabilistic analysis of algorithms, genetics, and evolution.

ENAS 508b, Responsible Conduct of Research  Staff
Required of first-year students. Presentation and discussion of topics and best practices relevant to responsible conduct of research including academic fraud and misconduct, conflict of interest and conflict of commitment, data acquisition and human subjects, use and care of animals, publication practices and responsible authorship, mentor/trainee responsibilities and peer review, and collaborative science. 0 Course cr

ENAS 509b, Electronic Materials: Fundamentals and Applications  Jung Han
Survey and review of fundamental issues associated with modern microelectronic and optoelectronic materials. Topics include band theory, electronic transport, surface kinetics, diffusion, materials defects, elasticity in thin films, epitaxy, and Si integrated circuits.

ENAS 510a, Physical and Chemical Basis of Bioimaging and Biosensing  Douglas Rothman
Basic principles and technologies for imaging and sensing the chemical, electrical, and structural properties of living tissues and biological macromolecules. Topics include magnetic resonance spectroscopy, MRI, positron emission tomography, and molecular imaging with MRI and fluorescent probes.

ENAS 517b / MCD 517b / PHYS 517b, Methods and Logic in Interdisciplinary Research  Corey O’Hern
This half-term PEB class is intended to introduce students to integrated approaches to research. Each week, the first of two sessions is student-led, while the second session is led by faculty with complementary expertise and discusses papers that use different approaches to the same topic (for example, physical and biological or experiment and theory). Counts as 0.5 credit toward graduate course requirements. ½ Course cr

ENAS 518a / MB&B 635a, Quantitative Approaches in Biophysics and Biochemistry  Julien Berro, Yong Xiong, and Nikhil Malvankar
The course offers an introduction to quantitative methods relevant to analysis and interpretation of biophysical and biochemical data. Topics covered include statistical testing, data presentation, and error analysis; introduction to dynamical systems; analysis of large datasets; and Fourier analysis in signal/image processing and macromolecular structural studies. The course also includes an introduction to basic programming skills and data analysis using MATLAB. Real data from research groups in MB&B are used for practice. Prerequisites: MATH 120 and MB&B 600 or equivalents, or permission of the instructors.

ENAS 519b, Responsible Conduct of Research  Staff
Required of first-year students in Chemical & Environmental Engineering, Electrical Engineering, and Mechanical Engineering & Materials Science. Presentation and discussion of topics and best practices relevant to responsible conduct of research including academic fraud and misconduct, conflict of interest and conflict of commitment, data acquisition and human subjects, use and care of animals, publication practices and responsible authorship, mentor/trainee responsibilities and peer review, and collaborative science. 0 Course cr

ENAS 521a, Classical and Statistical Thermodynamics  Michael Loewenberg
A unified approach to bulk-phase equilibrium thermodynamics, bulk-phase irreversible thermodynamics, and interfacial thermodynamics in the framework of classical thermodynamics, and an introduction to statistical thermodynamics. Both the activity coefficient and the equations of state are used in the description of bulk phases. Emphasis on classical thermodynamics of multicomponents, including concepts of stability and criticality, curvature effect, and gravity effect. The choice of Gibbs free energy function covers applications to a broad range of problems in chemical, environmental, biomedical, and petroleum engineering. The introduction includes theory of Gibbs canonical ensembles and the partition functions, fluctuations; Boltzmann statistics; Fermi-Dirac and Bose-Einstein statistics. Application to ideal monatomic and diatomic gases is covered.

ENAS 522a, Engineering and Biophysical Approaches to Cancer  Michael Mak
This course examines the current understanding of cancer as a complex disease and the advanced engineering and biophysical methods developed to study and treat this disease. All treatment methods are covered. Basic quantitative and computational backgrounds are required. Prerequisites: BENG 249 or equivalent and MATH 120 or equivalent.

ENAS 534a, Biomaterials  Anjelica Gonzalez
Introduction to materials, classes of materials from atomic structure to physical properties. Major classes of materials: metals, ceramics and glasses, and polymers, addressing their specific characteristics, properties, and biological applications. Throughout the presentation of the synthesis, characterization, and properties of the classes of materials, a connection is made to the selection of materials for use in specific biological applications by matching the material’s properties to those necessary for success in the application. Case studies address the successes and failures of particular materials from each of the classes in biological applications.
ENAS 535b / PATH 630b, Biomaterial-Tissue Interactions  Themis Kyriakides
Study of the interactions between tissues and biomaterials, with an emphasis on the importance of molecular- and cellular-level events in dictating the performance and longevity of clinically relevant devices. Attention to specific areas such as biomaterials for tissue engineering and the importance of stem/progenitor cells, as well as biomaterial-mediated gene and drug delivery.

ENAS 541b / CB&PB 523b / MB&B 523b / PHYS 52b, Biological Physics  Benjamin Machta
The course has two aims: (1) to introduce students to the physics of biological systems and (2) to introduce students to the basics of scientific computing. The course focuses on studies of a broad range of biophysical phenomena including diffusion, polymer statistics, protein folding, macromolecular crowding, cell motion, and tissue development using computational tools and methods. Intensive tutorials are provided for MATLAB including basic syntax, arrays, for-loops, conditional statements, functions, plotting, and importing and exporting data.

ENAS 544a, Fundamentals of Medical Imaging  Chi Liu
Review of basic engineering and physical principles of common medical imaging modalities including X-ray, CT, PET, SPECT, MRI, and echo modalities (ultrasound and optical coherence tomography). Additional focus on clinical applications and cutting-edge technology development.

ENAS 549b, Biomedical Data Analysis  Richard Carson
The course focuses on the analysis of biological and medical data associated with applications of biomedical engineering. It provides basics of probability and statistics, and analytical approaches for determination of quantitative biological parameters from noisy, experimental data. Programming in MATLAB to achieve these goals is a major portion of the course. Applications include Michaelis-Menten enzyme kinetics, Hodgkin-Huxley, neuroreceptor assays, receptor occupancy, MR spectroscopy, PET neuroimaging, brain image segmentation and reconstruction, and molecular diffusion.

ENAS 550a / C&MP 550a / MCDB 550a / PHAR 550a, Physiological Systems  Mark Saltzman and Stuart Campbell
The course develops a foundation in human physiology by examining the homeostasis of vital parameters within the body, and the biophysical properties of cells, tissues, and organs. Basic concepts in cell and membrane physiology are synthesized through exploring the function of skeletal, smooth, and cardiac muscle. The physical basis of blood flow, mechanisms of vascular exchange, cardiac performance, and regulation of overall circulatory function are discussed. Respiratory physiology explores the mechanics of ventilation, gas diffusion, and acid-base balance. Renal physiology examines the formation and composition of urine and the regulation of electrolyte, fluid, and acid-base balance. Organs of the digestive system are discussed from the perspective of substrate metabolism and energy balance. Hormonal regulation is applied to metabolic control and to calcium, water, and electrolyte balance. The biology of nerve cells is addressed with emphasis on synaptic transmission and simple neuronal circuits within the central nervous system. The special senses are considered in the framework of sensory transduction. Weekly discussion sections provide a forum for in-depth exploration of topics. Graduate students evaluate research findings through literature review and weekly meetings with the instructor.

ENAS 551b, Biotransport and Kinetics  Kathryn Miller-Jensen
Creation and critical analysis of models of biological transport and reaction processes. Topics include mass and heat transport, biochemical interactions and reactions, and thermodynamics. Examples from diverse applications, including drug delivery, biomedical imaging, and tissue engineering.

ENAS 553a, Immuno-Engineering  Tarek Fahmy
An advanced class that introduces immunology principles and methods to engineering students. The course focuses on biophysical principles and biomaterial applications in understanding and engineering immunity. The course is divided into three parts. The first part introduces the immune system: organs, cells, and molecules. The second part introduces biophysical characterization and quantitative modeling in understanding immune system interactions. The third part focuses on intervention, modulation, and techniques for studying the immune system with emphasis on applications of biomaterials for intervention and diagnostics.

ENAS 554b, Vascular Mechanics  Jay Humphrey
This course is designed to enable students to apply methods of continuum biomechanics to study diverse vascular conditions and treatments, including aging, atherosclerosis, aneurysms, effects of hypertension, design of tissue-engineered constructs, and vein grafts from an engineering perspective. Emphasis is placed on ensuring that the mechanics is driven by advances in the vascular mechanobiology.

ENAS 555b, Molecular and Cellular Biomechanics  Michael Murrell
The basic mechanical principles at the molecular and cellular level that underlie the major physical behaviors of the cell, from cell division to cell migration. Basic cellular physiology, methodology for studying cell mechanical behaviors, models for understanding the cellular response under mechanical stimulation, and the mechanical impact on cell differentiation and proliferation.

ENAS 556b, Introduction to Biomechanics  Michael Murrell
An introduction to the biomechanics used in biosolid mechanics, biofluid mechanics, biothermomechanics, and biochemomechanics. Diverse aspects of biomedical engineering, from basic mechanobiology to characterization of materials behaviors and the design of medical devices and surgical interventions.
ENAS 559a, Neuromuscular Biomechanics  Madhusudhan Venkadesan
Mechanics and control of animal movement, including skeletal muscle mechanics, systems-level neural and sensory physiology, elements of feedback control, and optimal control. Deriving equations of motion for multibody mechanical systems that are actuated by muscles or muscle-like motors; incorporating sensory feedback; analyzing system properties such as stability and energetics.

ENAS 561b / AMTH 76b / C&B B 562b / INP 562b / MB&B 562b / MCDB 562b / PHYS 562b, Modeling Biological Systems II  Damon Clark, Thierry Emonet, and Jonathan Howard
This course covers advanced topics in computational biology. How do cells compute, how do they count and tell time, how do they oscillate and generate spatial patterns? Topics include time-dependent dynamics in regulatory, signal-transduction, and neuronal networks; fluctuations, growth, and form; mechanics of cell shape and motion; spatially heterogeneous processes; diffusion. This year, the course spends roughly half its time on mechanical systems at the cellular and tissue level, and half on models of neurons and neural systems in computational neuroscience. Prerequisite: a 200-level biology course or permission of the instructor.

ENAS 567b, Systems Biology of Cell Signaling  Andre Levchenko
This course designed for graduate and advanced undergraduate students is focused on systems biology approaches to the fundamental processes underlying the sensory capability of individual cells and cell-cell communication in health and disease. The course is designed to provide deep treatment of both the biological underpinnings and mathematical modeling of the complex events involved in signal transduction. As such, it can be attractive to students of biology, bioengineering, biophysics, computational biology, and applied math. The course is part of the planned larger track in Systems Biology, being one of its final, more specialized courses. In spite of this, each lecture has a friendly introduction to the specific topic of interest, aiming to provide sufficient refreshment of the necessary knowledge. The topics have been selected to represent both cutting-edge directions in systems analysis of signaling processes and exciting settings to explore, making learning complex notions more enjoyable. Prerequisites: basic knowledge of biochemistry and cell biology, as well as programming experience and basic notions from probability theory and differential equations.

ENAS 570b / C&MP 560b / MCDB 560b / PHAR 560b, Cellular and Molecular Physiology: Molecular Machines in Human Disease  Emile Boulpaep
The course focuses on understanding the processes that transfer molecules across membranes at the cellular, molecular, biophysical, and physiological levels. Students learn about the different classes of molecular machines that mediate membrane transport, generate electrical currents, or perform mechanical displacement. Emphasis is placed on the relationship between the molecular structures of membrane proteins and their individual functions. The interactions among transport proteins in determining the physiological behaviors of cells and tissues are also stressed. Molecular motors are introduced and their mechanical relationship to cell function is explored. Students read papers from the scientific literature that establish the connections between mutations in genes encoding membrane proteins and a wide variety of human genetic diseases.

ENAS 575a / CPSC 575a, Computational Vision and Biological Perception  Steven Zucker
An overview of computational vision with a biological emphasis. Suitable as an introduction to biological perception for computer science and engineering students, as well as an introduction to computational vision for mathematics, psychology, and physiology students.

ENAS 585b, Fundamentals of Neuroimaging  Fahmeed Hyder
The neuroenergetic and neurochemical basis of several dominant neuroimaging methods, including fMRI. Topics range from technical aspects of different methods to interpretation of the neuroimaging results. Controversies and/or challenges for application of fMRI and related methods in medicine are identified.

ENAS 600a or b, Computer-Aided Engineering  Staff
Aspects of computer-aided design and manufacture (CAD/CAM). The computer's role in the mechanical design and manufacturing process; commercial tools for two- and three-dimensional drafting and assembly modeling; finite-element analysis software for modeling mechanical, thermal, and fluid systems.

ENAS 602a, Chemical Reaction Engineering  Eric Altman
Applications of physical-chemical and chemical-engineering principles to the design of chemical process reactors. Ideal reactors treated in detail in the first half of the course, practical homogeneous and catalytic reactors in the second.

ENAS 603a, Energy, Mass, and Momentum Processes  Amir Haji Akbari Balou
Application of continuum mechanics approach to the understanding and prediction of fluid flow systems that may be chemically reactive, turbulent, or multiphase.

ENAS 604b, Nanotechnology for Energy  Shu Hu
This is a comprehensive course with content at the intersection of nanoscale science, engineering, and technology, including application areas and nanofabrication technique. Topics include nanoscaled photovoltaic cells, hydrogen storage, fuel cells, and nanoelectronics; layer-by-layer assembly; organic-inorganic mesostructures; colloidal crystals, organic monolayers, proteins, DNA and abalone shells; synthesis of carbon nanotubes, nanowire, and nanocrystals; microelectromechanical systems (MEMs) devices; photolithography, electron beam lithography, and scanning probe lithography; lithium-based batteries; and nanomanufacturing (roll to roll, nanoimprint lithography, inkjet printing).

ENAS 624a, Chemical Engineering Process Control  Eric Altman
Transient regime modeling and simulations of chemical processes. Conventional and state-space methods of analysis and control design. Applications of modern control methods in chemical engineering. Course work includes a design project.
ENAS 638a, Water Chemistry  John Fortner
Aqueous inorganic chemistry for environmental engineering. Topics include acid-base chemistry, alkalinity, the carbonate system, speciation, precipitation/dissolution, redox chemistry, Eh/pH diagrams.

ENAS 640b, Aquatic Chemistry  Gaboury Benoit
A detailed examination of the principles governing chemical reactions in water. Emphasis is on developing the ability to predict the aqueous chemistry of natural and perturbed systems based on a knowledge of their biogeochemical setting. Focus is on inorganic chemistry, and topics include elementary thermodynamics, acid-base equilibria, alkalinity, speciation, solubility, mineral stability, redox chemistry, and surface complexation reactions. Illustrative examples are taken from the aquatic chemistry of estuaries, lakes, rivers, wetlands, soils, aquifers, and the atmosphere. A standard software package used to predict chemical equilibria may also be presented.

ENAS 641a, Biological Processes in Environmental Engineering  Jordan Peccia
Fundamental aspects of microbiology and biochemistry, including stoichiometry, kinetics, and energetics of biochemical reactions, microbial growth, and microbial ecology, as they pertain to biological processes for the transformation of environmental contaminants; principles for analysis and design of aerobic and anaerobic processes, including suspended- and attached-growth systems, for treatment of conventional and hazardous pollutants in municipal and industrial wastewaters and in groundwater.

ENAS 642b, Environmental Physicochemical Processes  Menachem Elimelech
Fundamental and applied concepts of physical and chemical ("physicochemical") processes relevant to water quality control. Topics include chemical reaction engineering, overview of water and wastewater treatment plants, colloid chemistry for solid-liquid separation processes, physical and chemical aspects of coagulation, coagulation in natural waters, filtration in engineered and natural systems, adsorption, membrane processes, disinfection and oxidation, disinfection by-products.

ENAS 649a, Policy Modeling  Edward Kaplan
Building on earlier course work in quantitative analysis and statistics, Policy Modeling provides an operational framework for exploring the costs and benefits of public policy decisions. The techniques employed include "back of the envelope" probabilistic models, Markov processes, queuing theory, and linear/integer programming. With an eye toward making better decisions, these techniques are applied to a number of important policy problems. In addition to lectures, assigned articles and text readings, and short problem sets, students are responsible for completing a take-home midterm exam and a number of cases. In some instances, it is possible to take a real problem from formulation to solution, and compare the student’s own analysis to what actually happened. Prerequisites: Decision Analysis and Game Theory, Data Analysis and Statistics, or a demonstrated proficiency in quantitative methods.

ENAS 660b, Green Engineering and Sustainability  Julie Zimmerman
This hands-on course highlights the key approaches to advancing sustainability through engineering design. The class begins with discussions on sustainability, metrics, general design processes, and challenges to sustainability. The current approach to design, manufacturing, and disposal is discussed in the context of examples and case studies from various sectors. This provides a basis for what and how to consider when designing products, processes, and systems to contribute to furthering sustainability. The fundamental engineering design topics to be addressed include toxicity and benign alternatives, pollution prevention and source reduction, separations and disassembly, material and energy efficiencies and flows, systems analysis, biomimicry, and life cycle design, management, and analysis. Students tackle current engineering and product design challenges in a series of class exercises and a final design project.

ENAS 711b, Biomedical Microtechnology and Nanotechnology  Rong Fan
Principles and applications of micro- and nanotechnologies for biomedicine. Approaches to fabricating micro- and nanostructures. Fluid mechanics, electrokinetics, and molecular transport in microfluidic systems. Integrated biosensors and microTAS for laboratory medicine and point-of-care uses. High-content technologies including DNA, protein microarrays, and cell-based assays for differential diagnosis and disease stratification. Emerging nanobiotechnology for systems medicine. Prerequisites: CHEM 112a, 114a, or 118a, and ENAS 194a or b.

ENAS 725b / APHY 725b, Advanced Synchrotron Techniques and Electron Spectroscopy of Materials  Charles Ahn
This course provides descriptions of advanced concepts in synchrotron X-ray and electron-based methodologies for studies of a wide range of materials at atomic and nano-scales. Topics include X-ray and electron interactions with matter, X-ray scattering and diffraction, X-ray spectroscopy and inelastic methods, time-resolved applications, X-ray imaging and microscopy, photo-electron spectroscopy, electron microscopy and spectroscopy, among others. Emphasis is on applying the fundamental knowledge of these advanced methodologies to real-world materials studies in a variety of scientific disciplines.

ENAS 748a, Applied Numerical Methods for Differential Equations  Beth Anne Bennett
The derivation, analysis, and implementation of numerical methods for the solution of ordinary and partial differential equations, both linear and nonlinear. Additional topics such as computational cost, error estimation, and stability analysis are studied in several contexts throughout the course. ENAS 747 is not a prerequisite.

ENAS 758b, Multiscale Models of Biomechanical Systems  Stuart Campbell
Current methods for simulating biomechanical function across biological scales, from molecules to organ systems of the human body. Theory and numerical methods; case studies exploring recent advances in multiscale biomechanical modeling. Includes computer laboratory sessions that introduce relevant software packages.
ENAS 778a, Advanced Robotic Mechanisms  Aaron Dollar

ENAS 805b, Biotechnology and the Developing World  Anjelica Gonzalez
This interactive course explores how advances in biotechnology enhance the quality of life in the developing world. Implementing relevant technologies in developing countries is not without important challenges; technical, practical, social, and ethical aspects of the growth of biotechnology are explored. Readings from Biomedical Engineering for Global Health as well as recent primary literature; case studies, in-class exercises, and current events presentations. Guest lecturers include biotechnology researchers, public policy ethicists, preventive research physicians, public-private partnership specialists, and engineers currently implementing health-related technologies in developing countries.

ENAS 806b, Photovoltaic Energy  Fengnian Xia
Electricity from photovoltaic solar cells is receiving increasing attention due to growing world demand for clean power sources. This course primarily emphasizes device physics of photovoltaics; statistics of charge carriers in and out of equilibrium; design of solar cells; and optical, electrical, and structural properties of semiconductors relevant to photovoltaics. Two laboratory sessions and a final project aid students in understanding both the applications and limitations of photovoltaic technology. The main objectives of this course are to equip students with the necessary background and analytical skills to understand and assess established and emerging photovoltaic technologies; to familiarize students with the diverse range of photovoltaic materials; and to connect materials properties to aspects of cell design, processing, and performance.

ENAS 825a, Physics of Magnetic Resonance Spectroscopy in Vivo  Graeme Mason
The physics of chemical measurements performed with nuclear magnetic resonance spectroscopy, with special emphasis on applications to measurement studies in living tissue. Concepts that are common to magnetic resonance imaging are introduced. Topics include safety, equipment design, techniques of spectroscopic data analysis, and metabolic modeling of dynamic spectroscopic measurements.

ENAS 850a, Solid State Physics I  Sohrab Ismail-Beigi
A two-term sequence (with ENAS 851) covering the principles underlying the electrical, thermal, magnetic, and optical properties of solids, including crystal structures, phonons, energy bands, semiconductors, Fermi surfaces, magnetic resonance, phase transitions, and superconductivity.

ENAS 851b, Solid State Physics II  Michel Devoret
A two-term sequence (with ENAS 850) covering the principles underlying the electrical, thermal, magnetic, and optical properties of solids, including crystal structures, phonons, energy bands, semiconductors, Fermi surfaces, magnetic resonance, phase transitions, and superconductivity.

ENAS 876a, Silicon Compilation  Rajit Manohar
A course for seniors and first-year graduate students on compiling computations into digital circuits using asynchronous design techniques. Emphasis is on the synthesis of circuits that are robust to uncertainties in gate and wire delays by the process of program transformations. Topics include circuits as concurrent programs, delay-insensitive design techniques, synthesis of circuits from programs, timing analysis and performance optimization, pipelining, and case studies of complex asynchronous designs.

ENAS 902a, Linear Systems  A. Stephen Morse
Background linear algebra; finite-dimensional, linear-continuous, and discrete dynamical systems; state equations, pulse and impulse response matrices, weighting patterns, transfer matrices. Stability, Lyapunov's equation, controllability, observability, system reduction, minimal realizations, equivalent systems, McMillan degree, Markov matrices. Recommended for all students interested in feedback control, signal and image processing, robotics, econometrics, and social and biological networks.

ENAS 905a, Applied Digital Signal Process  J. Rimas Vaǐnys

ENAS 912a, Biomedical Image Processing and Analysis  James Duncan and Lawrence Staib
A study of the basic computational principles related to processing and analysis of biomedical images (e.g., magnetic resonance, computed X-ray tomography, fluorescence microscopy). Basic concepts and techniques related to discrete image representation, multidimensional frequency transforms, image enhancement/restoration, image segmentation, and image registration.

ENAS 936a, Systems and Control  Kumpati Narendra
Design of feedback control systems with applications to engineering, biological, and economic systems. Topics include stat-space representation, stability, controllability, and observability of discrete-time systems; system identification; optimal control of systems with multiple outputs.

ENAS 940a, Neural Networks and Learning Systems  Staff
Neural networks (NNs) have become all-pervasive, giving us self-driving cars, Siri voice assistant, Alexa, and many more. While deep NNs deliver state-of-the-art accuracy on many artificial intelligence tasks, it comes at the cost of high computational complexity. Accordingly, designing efficient hardware architectures for deep neural networks is an important step toward enabling the wide deployment of NNs, particularly in low-power computing platforms, such as mobiles, embedded Internet of Things (IoT), and drones. This course aims to provide a thorough overview of deep learning techniques, while highlighting the key trends and advances toward efficient processing of deep learning in hardware systems, considering algorithm-hardware co-design techniques. Prerequisite: prior exposure to probability/linear algebra/matrix operations at basic undergraduate level is expected. Prior knowledge of programming
language like Python NumPy is useful. Familiarity with digital system design with basic understanding of logic, memory, and related design components is expected.

**ENAS 951b / CPSC 556b, Wireless Technologies and the Internet of Things**  Wenjun Hu
Fundamental theory of wireless communications and its application explored against the backdrop of everyday wireless technologies such as WiFi and cellular networks. Channel fading, MIMO communication, space-time coding, opportunistic communication, OFDM and CDMA, and the evolution and improvement of technologies over time. Emphasis on the interplay between concepts and their implementation in real systems. The labs and homework assignments require Linux and MATLAB skills and simple statistical and matrix analysis (using built-in MATLAB functions).

**ENAS 952a, Internet Engineering**  Leandros Tassiulas

**ENAS 963b, Network Algorithms and Stochastic Optimization**  Leandros Tassiulas
This course focuses on resource allocation models as well as associated algorithms and design and optimization methodologies that capture the intricacies of complex networking systems in communications computing as well as transportation, manufacturing, and energy systems. Max-weight scheduling, back-pressure routing, wireless opportunistic scheduling, time-varying topology network control, and energy-efficient management are sample topics to be considered, in addition to Lyapunov stability and optimization, stochastic ordering, and notions of fairness in network resource consumption.

**ENAS 968a, Cloud FPGA**  Jakub Szefer
An intermediate- to advanced-level course focusing on digital design and use of Field Programmable Gate Arrays (FPGAs). In addition, it centers around the new computing paradigm of Cloud FPGAs, where the FPGAs are hosted remotely by cloud providers and accessed remotely by users. The theoretical aspects of the course focus on digital system modeling and design using the Verilog Hardware Description Language (Verilog HDL). Students learn about logic synthesis, behavioral modeling, module hierarchies, combinatorial and sequential primitives, and implementing and testing the designs in simulation and real FPGAs. Students also learn about FPGA tools from two major vendors: Xilinx and Intel (formerly Altera). The practical aspects focus on designing systems using commercial Cloud FPGA infrastructures: Amazon F1 service (Xilinx FPGAs) or through the Texas Advanced Computing Center (Intel FPGAs). Students learn about cloud computing; interfacing servers to FPGAs, PCIe, and AXI protocols; and how to write software that runs on the cloud servers and leverages the FPGAs for acceleration of various computations. The course features a half-term project where students design, implement, test, and evaluate an accelerator design, such as Bitcoin miner, deep neural network computations, cryptographic circuits, or others. Prerequisites: familiarity with digital design basics and some experience with HDLs such as Verilog or VHDL.

**ENAS 986b, Semiconductor Silicon Devices and Technology**  Tso-Ping Ma
Introduction to integrated circuit technology, theory of solid state devices, and principles of device design and fabrication. Laboratory involves the fabrication and analysis of semiconductor devices, including Ohmic contacts, Schottky diodes, p-n junctions, MOS capacitors, MOSFETs, and integrated circuits.

**ENAS 990a or b, Special Investigations**  Staff
Faculty-supervised individual projects with emphasis on research, laboratory, or theory. Students must define the scope of the proposed project with the faculty member who has agreed to act as supervisor, and submit a brief abstract to the director of graduate studies for approval.

**ENAS 991a / MB&B 591a / MCDB 591a / PHYS 991a, Integrated Workshop**  Corey O’Hern
This required course for students in the PEB graduate program involves a series of modules, co-taught by faculty, in which students from different academic backgrounds and research skills collaborate on projects at the interface of physics, engineering, and biology. The modules cover a broad range of PEB research areas and skills. The course starts with an introduction to MATLAB, which is used throughout the course for analysis, simulations, and modeling.