ENGINEERING & APPLIED SCIENCE

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

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Mitchell Smooke

Deputy Dean
Vincent Wilczynski

BIOMEDICAL ENGINEERING

Chair
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Associate Professors Joerg Bewersdorf (Cell Biology), Stuart Campbell, Michael Choma, Tarek Fahmy, Rong Fan, Anjelica Gonzalez, Themis Kyriakides (Pathology), Chi Liu, Kathryn Miller-Jensen

Assistant Professors Michael Mak, Michael Murrell, Steven Tommasini, Jiangbing Zhou

CHEMICAL & ENVIRONMENTAL ENGINEERING

Chair
Jaehong Kim

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Professors Eric Altman, Paul Anastas, Michelle Bell, Ruth Blake, Menachem Elimelech, Gary Haller (Emeritus), Edgar Hertwich, Edward Kaplan, Jaehong Kim, Michael Loewenberg, Andrew Miranker, Jordan Peccia, Lisa Pfefferle, Daniel Rosner (Emeritus), W. Mark Saltzman, Udo Schwarz, T. Kyle Vanderlick, Paul Van Tassel, Julie Zimmerman

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

Lecturers Aniko Bezur, Katherine Schilling, Paul Whitmore

COMPUTER SCIENCE

Chair
Zhong Shao

Director of Graduate Studies
Vladimir Rokhlin (108 AKW, 203.432.1283, vladimir.rokhlin@yale.edu)

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Associate Professor Mahesh Balakrishnan

Assistant Professors Wenjun Hu,* Julian Jara-Ettinger,* Amin Karbasi,* Smita Krishnaswamy,* Sahand Negahban,* 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

Director of Graduate Studies
Hong Tang (hong.tang@yale.edu)

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), Fengnian Xia

Assistant Professors Wenjun Hu, Amin Karbasi, Jakub Szefer

MECHANICAL ENGINEERING & MATERIALS SCIENCE

Chair
Udo Schwarz

Director of Graduate Studies
Jan Schroers (jan.schroers@yale.edu)


Associate Professor Aaron Dollar

Assistant Professors Eric Brown, Judy Cha, Rebecca Kramer-Bottiglio, Madhusudhan Venkadesan

Lecturers Beth Anne Bennett, 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, biomolecular engineering, 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** Suspending; electrospay 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 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 550), 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) Two of the following three courses: Introduction to VLSI System Design (ENAS 875), Computer Architectures for Cognitive Processing and Machine Learning (ENAS 907), Computer Organization and Architecture (ENAS 967).

Electrical Engineering (Microelectronics track) Two of the following four courses: Physics and Devices of Optical Communication (ENAS 511), Heterojunction Devices (ENAS 718), Solid State Physics I (ENAS 850), Semiconductor Silicon Devices and Technology (ENAS 868).

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 793), 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.

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 208267, New Haven CT 06520-8267; 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 http://courses.yale.edu for the most updated course listing.

ENAS 500b, Mathematical Methods I 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  Yihong Wu
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  Evan Morris
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.  o Course cr

ENAS 509a, 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 511b, Physics and Devices of Optical Communication  Jung Han
A survey of the enabling components and devices that constitute modern optical communication systems. Focus on the physics and principles of each functional unit, its current technological status, design issues relevant to overall performance, and future directions. Permission of the instructor required.

ENAS 518a / MB&B 635a, Quantitative Approaches in Biophysics and Biochemistry  Julien Berro, Yong Xiong, and Jonathon Howard
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  Vincent Wilczynski
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.  o 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 530a, Optimization Techniques  Sekhar Tatikonda
Fundamental theory and algorithms of optimization, emphasizing convex optimization. The geometry of convex sets, basic convex analysis, the principle of optimality, duality. Numerical algorithms: steepest descent, Newton's method, interior point methods, dynamic programming, unimodal search. Applications from engineering and the sciences.

ENAS 534a, Biomaterials  Angelica 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 541b / CB&K 523b / MB&B 523b / PHYS 523b, Biological Physics  Simon Mochrie
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, Dana Peters, and Gigi Galiana
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 540b, 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 / MCB 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 558a, Introduction to Biomechanics  Michael Murrell
An introduction to the biomechanics used in biosolid mechanics, biofluid mechanics, biothermomechanics, and biochemomechanics. Diverse aspects of biomechanical 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, Dynamical Systems in Biology  Thierry Emonet and Jonathon 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: MCDB 561 or equivalent, or 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 class 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 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 573a / CPSC 573a, 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 576b / AMTH 667b / CPSC 576b, Advanced Computational Vision
   Steven Zucker
Advanced view of vision from a mathematical, computational, and neurophysiological perspective. Emphasis on differential geometry, machine learning, visual psychophysics, and advanced neurophysiology. Topics include perceptual organization, shading, color, and texture.

ENAS 600a, Computer-Aided Engineering
   Marshall Long
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
   Lisa Pfefferle
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 606a, Polymer Physics
   Mingjiang Zhong
A graduate-level introduction to the physics and physical chemistry of macromolecules. This course covers the static and dynamic properties of polymers in solution, melt and surface adsorbed states and their relevance in industrial polymer processing, nanotechnology, materials science, and biophysics. Starting from basic considerations of polymerization mechanisms, control of chain architecture, and a survey of polymer morphology, the course also extensively addresses experimental methods for the study of structure and dynamics via various scattering (light, x-ray, neutron) and spectroscopic methods (rheology, photon correlation spectroscopy) as integral components of polymer physics.

ENAS 609b, 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 611a, Separation Processes
   Paul Van Tassel
Theory and design of separation processes for multicomputer and/or multiphase mixtures via equilibrium and rate phenomena. Included are single-stage and cascaded absorption, adsorption, extraction, distillation, filtration, and crystallization processes.

ENAS 615b, Synthesis of Nanomaterials
   Lisa Pfefferle
This course focuses on the synthesis and engineering of nanomaterials. We also introduce different types of nanomaterials, unique properties at the nanoscale, measurement, and important applications of nanomaterials (including biomedical, electronic, and energy applications). Synthesis methods covered include gas phase and high vacuum techniques (CVD, MOCVD) as well as wet chemistry techniques such as reduction of metal salts, sonochemistry, and sol gel methods. Taking sample applications, we discuss the properties necessary for each, and how to control these properties through synthesis control, such as by using templating methods.

ENAS 626a, 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 640a, 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
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 648a, Environmental Transport Processes  Menachem Elimelech
Analysis of transport phenomena governing the fate of chemical and biological contaminants in environmental systems. Emphasis on quantifying contaminant transport rates and distributions in natural and engineered environments. Topics include distribution of chemicals between phases; diffusive and convective transport; interfacial mass transfer; contaminant transport in groundwater, lakes, and rivers; analysis of transport phenomena involving particulate and microbial contaminants.

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, queueing 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 673b, Air Quality and Energy  Drew Gentner
The production and use of energy are among the most important sources of air pollution worldwide. It is impossible to effectively address the impacts and regulation of air quality without understanding the impacts and behavior of emissions from energy sources. Through an assessment of emissions and physical/chemical processes, the course explores advanced topics (at the graduate level) on the behavior of pollutants from energy systems in the atmosphere. Topics include traditional and emerging energy technology, climate change, atmospheric aerosols, tropospheric ozone, as well as transport/modeling/mitigation.

ENAS 642b, Environmental Transport 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 643a, Introduction to Nanomaterials and Nanotechnology  Jeeyoung Cha
Survey of nanomaterial synthesis methods and current nanotechnologies. Approaches to synthesizing nanomaterials; characterization techniques; device applications that involve nanoscale effects.

ENAS 718b, Heterojunction Devices  Mark Reed
Advanced course in semiconductor heterojunction physics and devices. Topics include compound semiconductor material properties and growth techniques; high speed and millimeter-wave devices; quantum well and superlattice devices; device modeling; and a small laboratory component involving device fabrication and measurements.

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 747a, Applied Numerical Methods for Algebraic Systems, Eigensystems, and Function Approximation  Beth Anne Bennett
The derivation, analysis, and implementation of various numerical methods. Topics include root-finding methods, numerical solution of systems of linear and nonlinear equations, eigenvalue/eigenvector approximation, polynomial-based interpolation, and numerical integration. Additional topics such as computational cost, error analysis, and convergence are studied in several contexts throughout the course.
ENAS 748b, 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 770b, Soft Robot Modeling and Control  Rebecca Kramer-Bottiglio
This course covers topics including robot kinematics, elastic materials models, conductive composites, responsive material actuators, simple controllers, and physics-based soft robot simulation. The course also includes a project. Projects must involve theoretical modeling, design implementation, and/or experimental testing of a scientific hypothesis, and must have a mechanics and/or materials component. Prerequisites: prior course work in solid mechanics and familiarity with MATLAB.

ENAS 787b, Forces on the Nanoscale  Udo Schwarz
Modern materials science often exploits the fact that atoms located at surfaces or in thin layers behave differently from bulk atoms to achieve new or greatly altered material properties. The course provides an in-depth discussion of intermolecular and surface forces, which determine the mechanical and chemical properties of surfaces. In the first part, we discuss the fundamental principles and concepts of forces between atoms and molecules. Part two generalizes these concepts to surface forces. Part three then gives a variety of examples. The course is of interest to students studying thin-film growth, surface coatings, mechanical and chemical properties of surfaces, soft matter including biomembranes, and colloidal suspensions.

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 848a or b / PHYS 528a or b, Soft Condensed Matter Physics  Staff
An introduction to the physics and phenomenology of soft condensed matter: classical systems with mesoscale structure where thermal fluctuations and interfacial forces play fundamental roles. Discussion of applications to materials science/engineering, nanotechnology, and molecular/cellular biology. Essential concepts from statistical thermodynamics, classical mechanics, and electricity and magnetism are reviewed/developed as needed.

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  Vidvuds Ozolins
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 866a, CMOS Devices and Beyond  Tso-Ping Ma
The science and technology of modern CMOS devices and circuits, as well as emerging technologies. Topics may include basic CMOS device physics; interface properties of MOS structures; hot-carrier effects; experimental techniques to probe MOS parameters; and scaling of CMOS devices. In addition to weekly lectures, students are expected to make an in-depth study of a relevant topic (to be determined jointly with the instructor), write a term paper, and make an associated oral presentation to the class.

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 880a, Imaging Drugs in the Brain**  Evan Morris
Seminar course to explore the uses of functional imaging (PET and fMRI) to study the mechanisms of action and long-term effects of drugs (legal and illegal) on brain function. Basic research findings are the main topics, augmented by some discussion of imaging in drug development by Pharma. The central theme of the course is experiment design. How to design the proper imaging experiment to ask the question. What are the endpoints of the experiment? What are the limitations of interpretation? What are the proper controls and what are the proper analyses to ensure reliable, interpretable results? Syllabus is comprised primarily of classic journal articles, in addition to the occasional book chapter or review article. Most class periods begin with a short lecture to cover methodological concepts, followed by discussion of reading material. A number of class periods are organized as games, contests, or other in-class exercises. The emphasis is on formulating the question and designing the experiment. Topics include basic understanding of imaging technology (brief physics, biochemistry, and mathematics) as it relates to imaging of drugs, receptors, neurotransmitters; understanding the primary outcomes of imaging experiments; imaging experiment design; recent findings related to drug abuse; common neurophysiological pathways of addictive drugs (how to image reward); and uses of imaging in drug development (what do drug companies want to measure?). Weekly homework: concise written synopses of assigned articles (students routinely endorse the synopses as the best way to learn the material!)

**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 Vaišnys

**ENAS 907a, Computer Architectures and Artificial Intelligence**  Richard Lethin
Introduction to the development of computer architectures specialized for cognitive processing, both offline “thinking machines” as well as embedded devices. History of machines starting with early conceptions in defense systems to contemporary initiatives. Instruction sets, memory systems, parallel processing, analog architectures, probabilistic architectures, graph computing architectures, machine-learning architectures. Application and algorithm characteristics.

**ENAS 906a, 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 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, opportunitistic 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 954b, Information Theory**  Andrew Barron
Foundations of information theory in communications, statistical inference, statistical mechanics, probability, and algorithmic complexity. Quantities of information and their properties: entropy, conditional entropy, divergence, redundancy, mutual information, channel capacity. Basic theorems of data compression, data summarization, and channel coding. Applications in statistics.

**ENAS 956b, 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 990b, 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 / MCDB 591a / PHYS 991a, Integrated Workshop**  Corey O’Hern, Mark Gerstein, Scott Holley, Marcus Bosenberg, Madhusudhan Venkadesan, Michael Murrell, and Nikhil Malvankar
This required course for students in PEB involves hands-on laboratory modules with students working in pairs. A biology student is paired with a physics or engineering student; a computation/theory student is paired with an experimental student. The modules are devised so that a range of skills is acquired, and students learn from each other. Modules are hosted in faculty laboratories.