ENGINEERING & APPLIED SCIENCE

Dunham Laboratory, 203.432.4252
http://seas.yale.edu
M.S., M.Phil., Ph.D.

Dean
T. Kyle Vanderlick

Deputy Dean
Vincent Wilczynski

BIOMEDICAL ENGINEERING

Chair
Jay Humphrey

Director of Graduate Studies
Richard Carson (richard.carson@yale.edu)

Professors Richard Carson, Nicholas Christakis, James Duncan, Karen Hirschi, Jay Humphrey, Fahmeed Hyder, Andre Levchenko, Evan Morris, Laura Niklason, Douglas Rothman, W. Mark Saltzman, Martin Schwartz, Fred Sigworth, Brian Smith, Lawrence Staib, Hemant Tagare, Paul Van Tassel, Steven Zucker (Computer Science)

Associate Professors Joerg Bewersdorf (Cell Biology), Robin de Graaf, Tarek Fahmy, Rong Fan, Anjelica Gonzalez, Themis Kyriakides (Pathology), Kathryn Miller-Jensen, Xenophon Papademetris

Assistant Professors Stuart Campbell, Michael Choma, Chi Liu, Michael Mak, Michael Murrell, Steven Tommasini, Jiangbing Zhou

CHEMICAL & ENVIRONMENTAL ENGINEERING

Chair
Jaehong Kim

Director of Graduate Studies
Paul Van Tassel (paul.vantassel@yale.edu (paulvantassel@yale.edu))

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

Associate Professors Chinedum Osuji, André Taylor, Corey Wilson

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

Lecturers Aniko Bezur, Paul Whitmore

COMPUTER SCIENCE

Chair
Zhong Shao

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

Professors Dana Angluin, James Aspnes, Dirk Bergemann,* Ronald Coifman,* Julie Dorsey, Stanley Eisenstat, Joan Feigenbaum, Michael Fischer, David Gelernter, Mark Gerstein,* Rajit Manohar,* Drew McDermott, Dragomir Radev, Vladimir Rokhlin,† Holly Rushmeier, Brian Scassellati, Martin Schultz (Emeritus), Zhong Shao, Avi Silberschatz, Daniel Spielman, Leandros Tassiulas,* Y. Richard Yang, Steven Zucker†

Associate Professors Mahesh Balakrishnan, Minlan Yu

Assistant Professors Wenjun Hu,* Julian Jara-Ettinger,* Amin Karbasi,* Smita Krishnaswamy,* Sahand Negahban,* Ruzica Piskac, Mariana Raykova, Jakub Szefer*

Senior Lecturers Kyle Jensen,* Stephen Slade

Lecturers Benedict Brown, James Glenn, 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
Hongxing Tang (hong.tang@yale.edu)

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

Associate Professors Richard Lethin (Adjunct), Sekhar Tatikonda

Assistant Professors Wenjun Hu, Amin Karbasi, Jakub Szefer, Fengnian Xia

MECHANICAL ENGINEERING & MATERIALS SCIENCE

Chair
Udo Schwarz

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


Associate Professors Aaron Dollar, Corey O’Hern

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, modeling in mechanobiology, MRI, MRS, PET and modeling, nanomedicine, network analysis, the physics of image formation (MRI, optics, ultrasound, nuclear medicine, and X-ray), physiology and human factors engineering, systems biology, systems medicine, and tissue engineering and regenerative medicine.

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, 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 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 510), Physical and Chemical Basis of Bioimaging and Biosensing (ENAS 570). 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) Water Chemistry (ENAS 638), Biological Processes in Environmental Engineering (ENAS 641), Environmental Physicochemical Processes (ENAS 642). 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 Statistical Analysis in the Environmental Sciences (F&ES 758), Data Exploration and Analysis (S&DS 530), or Multivariate Statistics for 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: Photonics and Optical Electronics (ENAS 511), 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 Laboratory (CPSC 573), Classical and Statistical Thermodynamics (ENAS 521), Biological Physics (ENAS 541), Polymer Physics (ENAS 606), Synthesis of Nanomaterials (ENAS 645), 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—and Systems and Control (ENAS 936). 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://students.yale.edu/oci for the most updated course listing.

ENAS 500b / APHY 500b, Mathematical Methods I Paul Van Tassel
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 508b / APHY 508, Responsible Conduct of Research
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 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 511a, 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 513a, Introduction to Analysis  Peter Jones
Foundations of real analysis, including metric spaces and point set topology, infinite series, and function spaces.

ENAS 514b, Real Analysis  Staff
The Lebesgue integral, Fourier series, applications to differential equations.

ENAS 517b / MB&B 517b / MCDB 517b / PHYS 517b, Methods and Logic in Interdisciplinary Research  Staff
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 653a, Quantitative Approaches in Biophysics and Biochemistry  Nikhil Malvankar and Yong Xiong
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 521b, Classical and Statistical Thermodynamics  Shu Hu
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 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 630, Biomaterial-Tissue Interactions  Themis Kyriakides
The course addresses 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. In addition, specific areas such as biomaterials for tissue engineering and the importance of stem/progenitor cells, and biomaterial-mediated gene and drug delivery are addressed.

ENAS 541b / CB&RB 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 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 / M MDB 550a / PHAR 550a, Physiological Systems**  Mark Saltzman
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 556b, Molecular & Cellular Mechanics**  Michael Murrell

**ENAS 58a, 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 561b / AMTH 765b / CB&B 562b / INP 562b / MB&B 562b / MCDB 562b / PHYS 562b, Dynamical Systems in Biology**  Damon Clark, 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 567a, 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 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**  Frederick Sigworth
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 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 585b, Fundamentals of Neuroimaging  Fahmeed Hyder and Douglas Rothman
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 590b, Engineering Mathematics  J. Rimas Vaišnys
This course is designed for graduate students who have had an introduction to complex variables and partial differential equations. It explores features of complex functions useful in engineering applications and applies them to such problems as numerical transforms and their inversion, conformal mapping, and solution of Laplace equations in three dimensions. Mathematica, because it can provide seamless transitions between analytical, numerical, and graphical methods, is introduced and used extensively in the course. Prerequisite: ENAS 500 or equivalent.

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 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 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 645a, Industrial Ecology  Marian Chertow and Edgar Hertwich
Industrial ecology studies (1) the flows of materials and energy in industrial and consumer activities, (2) the effects of these flows on the environment, and (3) the influences of economic, political, regulatory, and social factors on the flow, use, and transformation of resources. The goals of the course are to define and describe industrial ecology; to demonstrate the relationships among production, consumption, sustainability, and industrial ecology in diverse settings, from firms to cities to international trade flows; to show how industrial ecology serves as a framework for the consideration of environmental and sustainability-related aspects of science, technology, and policy; and to define and describe tools, applications, and implications of industrial ecology.

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**  
Staff
This hands-on course highlights the key approaches to advancing sustainability through engineering design. The course 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 704b, Theoretical Fluid Dynamics**  
Juan Fernández de la Mora
Derivation of the equations of fluid motion from basic principles. Potential theory, viscous flow, flow with vorticity. Topics in hydrodynamics, gas dynamics, stability, and turbulence.

**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 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 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 848b / PHYS 528b, Soft Condensed Matter Physics**  
Eric Brown
An introduction to the physics and phenomenology of soft condensed matter: classical systems with mesoscale structure where thermal fluctuations and interfacial forces play essential 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 / APHY 548a / PHYS 548a, Solid State Physics I  Victor Henrich
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 / APHY 549b / PHYS 549b, 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 875a, Introduction to VLSI System Design  Rajit Manohar
Chip design. Provides background in integrated devices, circuits, and digital subsystems needed for design and implementation of silicon logic chips. Historical context, scaling, technology projections, physical limits. CMOS fabrication overview, complementary logical circuits, design methodology, computer-aided design techniques, timing, and area estimation. Case studies of recent research and commercial chips. Objectives of the course are (1) to give students the ability to complete the course project (design of a digital CMOS subsystem chip through layout), and (2) to understand the directions that future chip technologies may take. Selected projects are fabricated and packaged for testing by students. Prerequisite: circuits at the level of introductory physics and computer programming.

ENAS 900b, Distributed Computation and Decision Making  A. Stephen Morse
Within the field of network science there has long been interest in distributed computation and distributed decision-making problems of many types. Among these are consensus and flocking problems, the multi-robot rendezvous problem, distributed averaging, distributed solutions to linear algebraic equations, social networking problems, localization of sensors in a multisensor network, and the distributed management of robotic formations. The aim of this course is to explain what these problems are and to discuss their solutions. Related concepts from spectral graph theory, rigid graph theory, non-homogeneous Markov chain theory, stability theory, and linear system theory are covered. Prerequisite: although most of the mathematics needed are covered in the lectures, students taking this course should have a working understanding of basic linear algebra.

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 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 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 962a, Theoretical Challenges in Network Science  Amin Karbasi
This is an interdisciplinary course with a focus on the emerging science of complex networks and their mathematical models. Students learn about the recent research on the structure and analysis of such networks, and on models that abstract their basic properties. Topics include random graphs and their properties, probabilistic techniques for link analysis, centralized and decentralized search algorithms, random walks, diffusion and epidemic processes, and spectral methods.

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 967a, Computer Organization and Architecture  Jakub Szefer
Introduction to computer architecture, including computer organization, microprocessors, caches and memory hierarchies, I/O, and storage. Issues involving performance, energy, and security; processor benchmarking. Selected readings from current academic literature.

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, Lynne Regan, Simon Mochrie, Christine Jacobs-Wagner, Scott Holley, and Megan King
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.

ENAS 994b, Mechatronics Laboratory  Madhusudhan Venkadesan
Hands-on synthesis of control systems, electrical engineering, and mechanical engineering. Review of Laplace transforms, transfer functions, software tools for solving ODEs. Review of electronic components and introduction to electronic instrumentation. Introduction to sensors; mechanical power transmission elements; programming microcontrollers; PID control.