ENGINEERING & APPLIED SCIENCE

17 Hillhouse Avenue, 203.432.4220
http://seas.yale.edu
M.S., M.Phil., Ph.D.

Dean
Jeffrey Brock

Deputy Dean
Vincent Wilczynski

Assistant Dean
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APPLIED PHYSICS

Chair
Charles Ahn

Director of Graduate Studies
Vidvuds Ozolins (305 BCT and ESI, West Campus, vidvuds.ozolins@yale.edu)

Professors Charles Ahn, Sean Barrett (Physics), Hui Cao, Michel Devoret, Paul Fleury (Emeritus), Steven Girvin (Physics), Leonid Glazman (Physics), Jack Harris (Physics), Victor Henrich (Emeritus), Sohrab Ismail-Beigi, Marshall Long (Mechanical Engineering & Materials Science), Simon Mochrie, Corey O’Hern (Mechanical Engineering & Materials Science), Vidvuds Ozolins, Daniel Prober, Nicholas Read, Peter Schiffer, Robert Schoelkopf, Ramamurti Shankar (Physics), Mitchell Smooke (Mechanical Engineering & Materials Science), A. Douglas Stone, Hong Tang (Electrical Engineering), Robert Wheeler (Emeritus), Werner Wolf (Emeritus)

Associate Professors Michael Choma (Biomedical Engineering), Peter Rakich

Assistant Professors Yu He, Owen Miller, Shruti Puri

BIOMEDICAL ENGINEERING

Chair
Jay Humphrey

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

Professors Helene Benveniste,* Joerg Bewersdorf,* Richard Carson,† Nicholas Christakis,* Todd Constable,* Robin de Graaf,* James Duncan,‡ Jay Humphrey, Fahmeed Hyder,‡ Francis Lee,* Andre Levchenko, Graeme Mason,* Evan Morris,* Laura Niklason,* Xenophon Papademetris,* Douglas Rothman,† W. Mark Saltzman, Martin Schwartz,* Fred Sigworth,* Albert Sinusas,* Brian Smith,* Lawrence Staib,† Hemant Tagare,‡ Paul Van Tassel,* Steven Zucker‡

Associate Professors Stuart Campbell, Tarek Fahmy, Rong Fan, Gigi Galiana,* Anjelica Gonzalez, Michelle Hampson,* Henry Hsia,* Farren Issacs,* Themis Kyriakides,‡ Chi Liu,* Kathryn Miller-Jensen, Michael Murrell, Dana Peters,* Jiangbing Zhou*

Assistant Professors Nicha Dvornek,* Ansel Hillmer,* Michael Mak, Dustin Scheinost,* Gregory Tietjen*

* A secondary appointment with primary affiliation in another department or school.

† A joint appointment with another department.

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), 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 John Fortner, Drew Gentner

Assistant Professors Peijun Guo, Amir Haji-Akbari, Shu Hu, Mingjiang Zhong
**Lecturer** Katherine Schilling

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† A joint appointment with another school.

**COMPUTER SCIENCE**

**Chair**
Zhong Shao

**Director of Graduate Studies**
Vladimir Rokhlin (108 AKW, 203.432.1278, vladimir.rokhlin@yale.edu)


**Associate Professors** Abhishek Bhattacharjee, Theodore Kim, Smita Krishnaswamy,* Sahand Negahban,* Charalampos Papamanthou, Ruzica Piskac, Philipp Strack,* Jakub Szefer*

**Assistant Professors** Yang Cai, Wenjun Hu,* Julian Jara-Ettinger,* Amin Karbasi,* Anurag Khandelwal, Robert Soulé, David van Dijk,* Marynel Vázquez, Andre Wibisono

**Senior Lecturers** James Glenn, Kyle Jensen,* Stephen Slade

**Lecturers** Timothy Barron, Andrew Bridy,*† Rob Brunstad, Cody Murphy, Scott Petersen, Brad Rosen, Andrew Sherman,* Cecillia Xie

* A secondary appointment with primary affiliation in another department or school.

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**ELECTRICAL ENGINEERING**

**Chair**
Leandros Tassiulas

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

**Professors** Hui Cao,* James Duncan,† Jung Han, Roman Kuc, Richard Lethin (*Adjunct*), Rajit Manohar, A. Stephen Morse, Kumpati Narendra (*Emeritus*), Daniel Prober,*† Lawrence Staib,*† Hemant Tagare,* Hong Tang, Leandros Tassiulas, J. Rimas Vaisnys (*Emeritus*), Y. Richard Yang†

**Associate Professors** Amin Karbasi, Jakub Szefer, Fengnian Xia

**Assistant Professors** Wenjun Hu, Priyadarshini Panda

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**MECHANICAL ENGINEERING & MATERIALS SCIENCE**

**Chair**
Udo Schwarz

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


**Associate Professors** Judy Cha, Madhusudhan Venkadesan

**Assistant Professors** Rebecca Kramer-Bottiglio, Amir Pahlavan, Diana Qiu, Daniel Wiznia*

**Lecturers** Beth Anne Bennett, Jordan Booth, Joseph Zinter

* A secondary appointment with primary affiliation in another department or school.

† A joint appointment with another department.
Programs of study are offered in the areas of applied mechanics, applied physics, 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.

**APPLIED PHYSICS**

**Fields of Study**

Fields include areas of theoretical and experimental condensed-matter and materials physics, optical and laser physics, quantum engineering, and nanoscale science. Specific programs include surface and interface science, first principles electronic structure methods, photonic materials and devices, complex oxides, magnetic and superconducting artificially engineered systems, quantum computing and superconducting device research, quantum transport and nanotube physics, quantum optics, and random lasers.

**BIOMEDICAL ENGINEERING**

**Fields of Study**

Biological and medical devices, biological signals and sensors, biomaterials, biophotonics, cellular biomechanics, computational biomechanics, computational medicine, computer vision, digital image analysis and processing, drug delivery, energy metabolism, experimental biomechanics, gene delivery, gene therapy, image analysis, Magnetic Resonance Imaging (MRI), Magnetic Resonance Spectroscopy (MRS), modeling in mechanobiology, molecular biomechanics, nanomedicine, network analysis, neuroreceptors, physics of image formation (MRI, optics, ultrasound, nuclear medicine, and X-ray), physiology and human factors engineering, Positron Emission Tomography (PET), regenerative medicine, signaling pathways, Single Photon Emission Computed Tomography (SPECT), systems biology, systems medicine, tissue engineering, tracer kinetic modeling, and vascular biology.

**CHEMICAL & ENVIRONMENTAL ENGINEERING**

**Fields of Study**

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

**COMPUTER SCIENCE**

**Fields of Study**

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

**ELECTRICAL ENGINEERING**

**Fields of Study**

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

**MECHANICAL ENGINEERING & MATERIALS SCIENCE**

**Fields of Study**

**Fluids and thermal sciences** Electrospray theory and characterization; electrical propulsion applications; aerodynamic instrumentation for separation of clusters and aerosol particles; heterogeneous nucleation in the gas phase; combustion and flames; computational methods for fluid dynamics and reacting flows; laser diagnostics of reacting and nonreacting flows; interfacial flows and instabilities and transport phenomena in disordered media.

**Soft matter/complex fluids** Jamming and slow dynamics in gels, glasses, and granular materials; mechanical properties of soft and biological materials; rheology and statistical mechanics of muscle; structure and dynamics of proteins and other macromolecules and wetting of soft solids, elastocapillarity, and poroelasticity.

**Materials science** Studies of thin films; nanoscale effects on electronic, optical, and emergent properties of two-dimensional layered materials; picoscale characterization and engineering; correlated electron systems; molecular beam epitaxy; 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; nanostructured energy applications; nanoparticle synthesis for energy applications; combinatorial materials science; in situ transmission electron and scanning probe microscopy; theoretical spectroscopy and computational materials science; and halide perovskites.

**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; artificial muscle; soft-bodied control; electromechanical energy conversion; biomechanics of human movement and human-powered vehicles.

**Bioengineering** Engineering sciences of living systems; biomechanics; motor control; animal locomotion; cell and tissue mechanics; biomaterials and therapeutics; human health and orthopaedics; bio-inspired computation and design.

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

Students applying to the Ph.D. program in Applied Physics, 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 teaching fellows for up to two terms, 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 their 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 term 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

#### Applied Physics

See the departmental entry for Applied Physics in this bulletin.

**Biomedical Engineering** ENAS 410, ENAS 550. One of these courses may be taken in the second year. In addition, there is a math requirement that must be met by taking ENAS 500, ENAS 505, or ENAS 549 in the first year. Students enrolled in IGPPEB may also meet the math requirement by taking ENAS 541 or ENAS 561.

**Chemical & Environmental Engineering (Chemical track)** ENAS 500, ENAS 521, ENAS 602, ENAS 603.

**Chemical & Environmental Engineering (Environmental track)** ENAS 641, ENAS 642, and either ENAS 638 or ENAS 649. In addition, there is a math requirement that must be met by taking one of the following courses in the first year: ENAS 500, ENV 728, ENV 753, ENV 758, ENV 781, S&DS 530, S&DS 538, or S&DS 563.

#### Computer Science

See the departmental entry for Computer Science in this bulletin.

**Electrical Engineering (Computer Engineering track)** Competence must be demonstrated in at least two of the three research areas. At least two courses that cover two different areas are required. In the area of architecture, the course options are ENAS 907, ENAS 940, and ENAS 967. In the area of VLSI, the course options are ENAS 875 and ENAS 876. In the area of computer systems, the course options are CPSC 522, CPSC 523, CPSC 525, CPSC 526, CPSC 533, and ENAS 968.

**Electrical Engineering (Microelectronics track)** Two of the following four courses: ENAS 511, ENAS 718, ENAS 850, ENAS 986.
Electrical Engineering (System and Signals track) ENAS 502, ENAS 902.

Mechanical Engineering & Materials Science Students must demonstrate competence in one of five areas: Fluid and Thermal Sciences, Soft Matter/Complex Fluids, Materials Science, Robotics/Mechatronics, or Bioengineering. As a minimum requirement, students must take at least one of the following courses in the first year of study: CPSC 572, CPSC 573, ENAS 521, ENAS 541, ENAS 559, ENAS 606, ENAS 615, ENAS 703, ENAS 704, ENAS 708, ENAS 752, ENAS 755, ENAS 777, ENAS 778, ENAS 787, ENAS 848, ENAS 850, ENAS 851, ENAS 902 (if not used to satisfy the math requirement), ENAS 936, ENAS 944, PHYS 628. There is a math requirement that must be met by taking ENAS 500, ENAS 902, or PHYS 506, depending on the research area. In addition, students must take two terms of ENAS 700 during the first two years of study; this course does not count toward the ten-course requirement.

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

M.D./PH.D. STUDENTS
M.D./Ph.D. students affiliate with the Department of Biomedical Engineering via the School of Medicine. M.D./Ph.D. students officially affiliate with Biomedical Engineering after selecting a thesis adviser and consulting with the DGS.

The academic requirements for M.D./Ph.D. students entering Biomedical Engineering are modified from the normal requirements for Ph.D. students. Other than the modifications listed here, M.D./Ph.D. students in Biomedical Engineering are subject to all of the same requirements as the other graduate students in the department.

Courses Seven graduate-level courses taken for a grade must be completed during the first two years of the Ph.D. program. (One Yale graduate-level course taken for a grade during medical school may be counted toward this requirement at the discretion of the DGS.) There are three required courses: ENAS 510 and two terms of ENAS 990. All students are expected to present their Special Investigation work at a department symposium held on the last day of the reading period. In addition, there is a math requirement, which may be met by taking any one of the following courses: ENAS 500, ENAS 505, or ENAS 549. Among the three electives, one must be in engineering or a closely related field. Students must obtain a grade of Honors in any two of these courses, excluding ENAS 990, and maintain an average of at least High Pass.

Teaching Students are required to serve as a teaching fellow for up to two terms but are not permitted to teach during their first year of graduate study.

Prospectus and qualifying exam M.D./Ph.D. students must complete and submit their thesis prospectus by the end of the fifth term as an affiliated graduate student. Students who affiliate at the customary point of year three must submit the approved prospectus before the end of the fall term of the fifth year (at the beginning of year three as an affiliated Ph.D. student). After submitting the prospectus, students present their results to date and their proposed research to their thesis committee in an area examination. Students are given two opportunities to pass this exam.

Candidacy M.D./Ph.D. students will be admitted to candidacy once they have completed their course requirements, passed their qualifying exam, and had their dissertation prospectus approved by their advisory committee.

Further requirements M.D./Ph.D. students who are admitted to candidacy are required to have an annual Thesis Committee meeting. In the first year after admission to candidacy, students are expected to present their research work at a departmental seminar. Attendance at weekly Biomedical Engineering Seminars is mandatory. A final oral presentation of the dissertation research is required before students may submit to the Dissertation Office.

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 in Engineering & Applied Science. 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.

Joint Master’s Degree Program (School of Engineering & Applied Science and School of the Environment) The joint master’s degree program offered by the School of the Environment (YSE) and the School of Engineering & Applied Science (SEAS) provides environmental engineers and environmental managers with the opportunity to develop knowledge and tools to address the complex relationship between technology and the environment. This joint-degree program will train graduate students to design and manage engineered and natural systems that address critical societal challenges, while considering the complex technical, economic, and sociopolitical systems relationships. Each joint program leads to the simultaneous award of two graduate professional degrees: either the Master of Environmental Management (M.E.M.) or the Master of Environmental Science (M.E.Sc.) from YSE, and a Master of
Science (M.S.) from SEAS. Students can earn the two degrees concurrently in 2.5 years, less time than if they were pursued sequentially. Candidates spend the first year at YSE, the second year at SEAS, and their final term at YSE. Joint-degree students are guided in this process by advisers in both YSE and SEAS. Candidates must submit formal applications to both YSE and SEAS and be admitted separately to each School, i.e., each School makes its decision independently. It is highly recommended that students apply to and enter a joint-degree program from the outset, although it is possible to apply to the second program once matriculated at Yale. Prospective students to the joint-degree program apply to the YSE master’s degree through YSE (https://apply.environment.yale.edu/apply) and to the SEAS master’s degree in Chemical & Environmental Engineering through the Graduate School of Arts and Sciences (https://gfas.yale.edu/admissions/degree-program-application-process).

The following six courses are required of all joint-degree YSE/SEAS master’s students completing their M.S. in Environmental Engineering: ENAS 641, ENAS 642, ENAS 660, ENV 773, ENV 838, and either ENV 712 or ENV 724. Two additional Yale-wide technical electives approved by the DGS (or faculty in an equivalent role in Environmental Engineering) are required. These courses may be cross-listed with or administered by YSE with prior approval from the DGS. For the joint-degree requirements for completion of the M.E.M. or M.E.Sc. in YSE, see the bulletin of the Yale School of the Environment at https://bulletin.yale.edu.

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

COURSES

The list of courses may be slightly modified by the time term begins. Please visit https://courses.yale.edu for the most updated course listing.

**ENAS 502b / S&DS 551b, Stochastic Processes**  Staff

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

**ENAS 508b, Responsible Conduct of Research**  Staff

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

**ENAS 509b, Electronic Materials**  Jung Han

Survey and review of fundamental material issues pertinent to modern microelectronic and optoelectronic technology. Topics include band theory, electronic transport, surface kinetics, diffusion, defects in crystals, thin film elasticity, crystal growth, and heteroepitaxy.

**ENAS 510a, Physical and Chemical Basis of Bioimaging and Biosensing**  Fahmeed Hyder, Ansel Hillmer, and Douglas Rothman

Basic principles and technologies for imaging and sensing the chemical, electrical, and structural properties of living tissues and biological macromolecules. Topics include magnetic resonance spectroscopy, MRI, positron emission tomography, and molecular imaging with MRI and fluorescent probes.

**ENAS 517b / MB&B 517b / MCDB 517b / PHYS 517b, Methods and Logic in Interdisciplinary Research**  Corey O’Hern

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

**ENAS 518a / MB&B 635a, Quantitative Approaches in Biophysics and Biochemistry**  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 519b, Responsible Conduct of Research**  Staff

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

**ENAS 520b, Classical and Statistical Thermodynamics**  Peijun Guo

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

ENAS 523a, Data and Clinical Decision-Making  John Onofrey and Michael Choma
Data and computation are reshaping medicine and clinical decision-making. Examples include acute states of physiological failure such as shock and sepsis as well as failure modes associated with aging (e.g., delirium/acute brain failure, falls). This seminar provides (1) a modern, clinically facing view of physiological failure and (2) a survey of how data and computation are reshaping clinical concepts and practice, including decision-making. Key topics and concepts include medical data types (e.g., imaging, lab values, oximetry); nonlinearity and complexity in physiological resilience and failure; clinically relevant AI/ML methods; data-driven definitions of medical disease; predictive modeling as a distinct field in AI/ML; and clinical decision-making using modern data and computational tools. The course is led by two instructors with complementary backgrounds that include AI/ML, statistics/data science, medical physiology, clinical medicine, and digital health. Guest lecturers from both clinical practice and industry provide additional context. Course work includes scientific literature review, written reports, oral presentations, and a final project. Students interested in AI/ML in medicine in both academic and industry settings with an engineering/medical background would benefit from this course. The course provide the requisite background for physiology and assumes a basic understanding of AI/ML but has no strict prerequisites.

ENAS 535b / PATH 630b, Biomaterial-Tissue Interactions  Themis Kyriakides
Study of the interactions between tissues and biomaterials, with an emphasis on the importance of molecular- and cellular-level events in dictating the performance and longevity of clinically relevant devices. Attention to specific areas such as biomaterials for tissue engineering and the importance of stem/progenitor cells, as well as biomaterial-mediated gene and drug delivery.

ENAS 541b / CB&B 523b / MB&B 523b / PHYS 533b, Biological Physics  Corey O’Hern
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 549a, 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  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 559a, 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 55a, Immunoeengineering  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 558b, 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, Modeling Biological Systems II**  Thierry Emonet, Joe Howard, and Damon Clark  
This course covers advanced topics in computational biology. How do cells compute, how do they count and tell time, how do they oscillate and generate spatial patterns? Topics include time-dependent dynamics in regulatory, signal-transduction, and neuronal networks; fluctuations, growth, and form; mechanics of cell shape and motion; spatially heterogeneous processes; diffusion. This year, the course spends roughly half its time on mechanical systems at the cellular and tissue level, and half on models of neurons and neural systems in computational neuroscience. Prerequisite: a 200-level biology course or permission of the instructor.

**ENAS 567b, Systems Biology of Cell Signaling**  Andre Levchenko  
This course designed for graduate and advanced undergraduate students is focused on systems biology approaches to the fundamental processes underlying the sensory capability of individual cells and cell-cell communication in health and disease. The course is designed to provide deep treatment of both the biological underpinnings and mathematical modeling of the complex events involved in signal transduction. As such, it can be attractive to students of biology, bioengineering, biophysics, computational biology, and applied math. The 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 568b, Topics in Immunoengineering**  Tarek Fahmy  
This course addresses the intersection of immunobiology with engineering and biophysics. It invokes engineering tools, such as biomaterials, solid-state devices, nanotechnology, biophysical chemistry, and chemical engineering, toward developing newer and effective solutions to cancer immunotherapy, autoimmune therapy, vaccine design, transplantation, allergy, asthma, and infections. The central theme is that dysfunctional immunity is responsible for a wide range of disease states and that engineering tools and methods can forge a link between the basic science and clinically translatable solutions that will potentially be “modern cures” to disease. This course is a follow-up to ENAS 553 and focuses more on the clinical translation aspect as well as new understandings in immunology and how they can be translated to the clinic and eventually to the market. Prerequisites: ENAS 553, differential equations, and advanced calculus.

**ENAS 569b, Single-Cell Biology, Technologies, and Analysis**  Rong Fan  
This course teaches the principles of single-cell heterogeneity in human health and disease as well as the cutting-edge wet-lab and computational techniques for single-cell analysis, with a particular focus on omics-level profiling and data analysis. Topics covered include single-cell-level morphometric analysis, genomic alteration analysis, epigenomic analysis, mRNA transcriptome sequencing, small RNA profiling, surface epitope, intracellular signaling protein and secreted protein analysis, metabolomics, multi-omics, and spatially resolved single-cell omics mapping. We also teach computational methods for quantification of cell types, states, and differentiation trajectories using single-cell high-dimensional data. Finally, case studies are provided to show the power of single-cell analysis in therapeutic target discovery, biomarker research, clinical diagnostics, and personalized medicine. Prerequisite: physiological systems, molecular biology, or biochemistry.

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

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

**ENAS 585b / INP 585b, Fundamentals of Neuroimaging**  Fahmeeed 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 600a or b, Computer-Aided Engineering  Ronald Adrezin
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 602b, Chemical Reaction Engineering  Eric Altman
Applications of physical-chemical and chemical-engineering principles to the design of chemical process reactors. Ideal reactors treated in detail in the first half of the course, practical homogeneous and catalytic reactors in the second.

ENAS 603b, Energy, Mass, and Momentum Processes  Michael Loewenberg
Application of continuum mechanics approach to the understanding and prediction of fluid flow systems that may be chemically reactive, turbulent, or multiphase.

ENAS 606b, Polymer Chemistry and 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 615a, Synthesis of Nanomaterials  Lisa Pfefeler
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 621a, Principles and Applications of Energy Technology  Shu Hu
This course covers a range of applications in energy supply and energy-efficient consumption, with a focus on the basic understanding of physical and chemical processes. How the energy technology provides sustainable planetary solutions is discussed. Course modules are arranged for the comparative study of solar-to-chemical and solar-to-electricity energy conversion processes, thus providing students an interdisciplinary perspective on electrochemistry, solid-state physics, photochemistry, and nanoscience. Topics include nanostructured solar cells, fuel cells, solar fuel devices, CO2 capture and utilization, petrochemical catalysis, solar-thermal combined cycles, and quantum phenomena in catalysis and surface sciences. These topics supplement the graduate study in energy conversion, energy storage, and nanoscale transport phenomena.

ENAS 638b, Environmental Organic Chemistry  Jordan Peccia
This course examines the major physical and chemical attributes and processes affecting the behavior of organic compounds in environmental systems, including volatilization, sorption/attachment, diffusion, and reactions. Emphasis is on anthropogenic hydrophobic organic compounds (e.g., TCE, PCBs, DDT) and less hydrophobic emerging contaminants of concern (e.g., pharmaceuticals, explosives, etc.). The course reviews basic concepts from physical chemistry and examines the relationships between chemical structure, properties, and environmental behavior of organic compounds. Physical and chemical processes important to the fate, treatment, and transformation of specific organic compounds are addressed, including solubility, volatilization, partitioning, sorption/attachment, bioaccumulation, and bulk environmental transformation pathways. Equilibrium and kinetic models based on these principles are used to predict the fate and transport of organic contaminants in the environment.

ENAS 641a, Biological Processes in Environmental Engineering  Menachem Elimelech
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 H Kaplan
Building on earlier course work in quantitative analysis and statistics, Policy Modeling provides an operational framework for exploring the costs and benefits of public policy decisions. The techniques employed include "back of the envelope" probabilistic models, Markov processes, queuing theory, and linear/integer programming. With an eye toward making better decisions, these techniques are applied to a number of important policy problems. In addition to lectures, assigned articles and text readings, and short problem sets, students are responsible for completing a take-home midterm exam and a number of cases. In some instances, it is possible to take a real problem from formulation to solution, and compare the student's own analysis to what actually happened. Prerequisites: Decision Analysis and Game Theory, Data Analysis and Statistics, or a demonstrated proficiency in quantitative methods.

ENAS 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 700a, Research Seminars in Mechanical Engineering & Materials Science  Jan Schroers
The purpose of this course is to introduce graduate students to state-of-the-art research in all areas of Mechanical Engineering & Materials Science (MEMS), as well as related disciplines, so that students understand the range of current research questions that are being addressed. An important goal is to encourage students to explore research topics beyond their particular field of study and develop the ability to contextualize their work in terms of larger research questions in MEMS. We therefore require that MEMS Ph.D. students enrolled in this course attend at least eight research seminars during the term: six must be part of the official MEMS seminar series, and two can be from any other relevant Yale graduate department/program seminar series. This course is graded Sat/Unsat with sign-in sheets used to monitor attendance. Required of first- and second-year MEMS Ph.D. students. 0 Course cr

ENAS 703a, Introduction to Nanomaterials and Nanotechnology  Judy Cha
Survey of nanomaterial synthesis methods and current nanotechnologies. Approaches to synthesizing nanomaterials; characterization techniques; device applications that involve nanoscale effects.

ENAS 718b, Advanced Electron Devices  Staff
The science and technology of semiconductor electron devices. Topics include compound semiconductor material properties and growth techniques; heterojunction, quantum well, and superlattice devices; quantum transport; graphene and other 2-D material systems.

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

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

ENAS 850a, Solid State Physics I Yu He
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 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 / INP 532a, Imaging Drugs in the Brain Evan Morris, Kelly Cosgrove, Michelle Hampson, and Bernadette Marquez-Nostra 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? The 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 900b, Decisions and Computations across Networks 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 907b / CPSC 549b, 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 940a, Neural Networks and Learning Systems Priya Panda
Neural networks (NNs) have become all-pervasive, giving us self-driving cars, Siri voice assistant, Alexa, and many more. While deep NNs deliver state-of-the-art accuracy on many artificial intelligence tasks, it comes at the cost of high computational complexity. Accordingly, designing efficient hardware architectures for deep neural networks is an important step toward enabling the wide deployment of NNs, particularly in low-power computing platforms, such as mobiles, embedded Internet of Things (IoT), and drones. This course aims to provide a thorough overview of deep learning techniques, while highlighting the key trends and advances toward efficient processing of deep learning in hardware systems, considering algorithm–hardware co-design techniques. Prerequisite: prior exposure to probability/linear algebra/matrix operations at basic undergraduate level is expected. Prior knowledge of programming
language like Python NumPy is useful. Familiarity with digital system design with basic understanding of logic, memory, and related design components is expected.

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

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

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

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

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

**ENAS 994b, Mechatronics Laboratory**  Staff  
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.