ENGINEERING & APPLIED SCIENCE

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

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APPLIED PHYSICS

Chair
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Associate Professors Michael Choma (*Biomedical Engineering*), Peter Rakich

Assistant Professors Yu He, Owen Miller, Shruti Puri

BIOMEDICAL ENGINEERING

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CHEMICAL AND ENVIRONMENTAL ENGINEERING

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COMPUTER SCIENCE

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Senior Lecturers James Glenn, Stephen Slade

Lecturers Timos Antonopoulos, Timothy Barron, Ozan Erat, Kyle Jensen,* Janet Kayfetz, Jay Lim, Dylan McKay, Cody Murphey, Sohee Park, Scott Petersen, Brad Rosen, Alan Weide, Cecillia Xie

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ELECTRICAL AND COMPUTER ENGINEERING

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Associate Professors Amin Karbasi, Jakub Szefer

Assistant Professors Dionysis Kalogerias, Mengxia Liu, Owen Miller,* Priyadarshini Panda, Shreya Saxena*

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MECHANICAL ENGINEERING AND MATERIALS SCIENCE

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Associate Professors Rebecca Kramer-Bottiglio, Madhusudhan Venkadesan

Assistant Professors Ian Abraham, Yimin Luo, Amir Pahlavan, Diana Qiu, Cong Su, Daniel Wiznia*

Senior Lecturer Beth Anne Bennett

Lecturers Joran Booth, Lawrence Wilen, 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, biomedical engineering, and personalized medicine and applied 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 AND ENVIRONMENTAL ENGINEERING

Fields of Study

Fields include nanomaterials, polymers, interfacial phenomena, energy, water and air quality, environmental microbiology, carbon capture, 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 AND COMPUTER 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, 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 AND 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; 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, poroelasticity, microrheology and scattering.

Materials science Studies of structure-property-processing relationships; 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; metallic glasses; sustainable metallurgy; data centered research approaches; nanomaterials; characterization of crystallization and other phase transformations; nanoimprinting; atomic-scale investigations of surface interactions and properties; classical and quantum nanomechanics; nanostructured energy applications; combinatorial materials science; data science in materials science; materials genome; 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; legged locomotion; multi-agent search and exploration; optimal control for learning; model-predictive control; reinforcement learning; 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; biomolecular structure; biomechanics; motor control; animal locomotion; cell and tissue mechanics; biomaterials and therapeutics; human health and orthopaedics; bio-inspired computation and design; biomaterials and cell-material interaction.

INTEGRATED GRADUATE PROGRAM IN PHYSICAL AND ENGINEERING BIOLOGY (PEB)

Students applying to the Ph.D. program in Applied Physics, Biomedical Engineering, Chemical and Environmental Engineering, and Mechanical Engineering and 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.

QUANTUM MATERIALS SCIENCE AND ENGINEERING (QMSE)

Students applying to the Ph.D. program in Applied Physics or Mechanical Engineering and Materials Science may also apply to be part of the QMSE program. See the description under Non-Degree-Granting Programs, Councils, and Research Institutes for course requirements.

SPECIAL REQUIREMENTS FOR THE PH.D. DEGREE

The online publication *Qualification Procedure for the Ph.D. Degree* describes in detail all requirements in Biomedical Engineering, Chemical and 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 and the Applied Physics departmental entry for special requirements for the Ph.D. in Applied Physics.

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, 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. During the first year, students are required to register for two Special Investigations; any additional terms of Special Investigations will not count toward the degree. At least two elective courses 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, and it is required that by the beginning of the third term, the faculty adviser provides the financial support indicated in the admissions offer letter, barring the award of external funding. 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 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 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 510, 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 and Environmental Engineering (Chemical track) ENAS 500, and two of the following three courses: ENAS 521, ENAS 602, ENAS 603.

Chemical and Environmental Engineering (Environmental track) ENAS 640, ENAS 641, ENAS 642. In addition, there is a math requirement that must be met by taking one of the following courses in the first year: ENAS 500, ENAS 748, ENV 758, or S&DS 530. Any other mathematics or statistics class can be taken as an elective in addition to one of these core classes.

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

Electrical Engineering Courses will be assigned by the adviser in coordination with the research committee, and are subject to approval by the DGS.

Mechanical Engineering and 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 559, CPSC 570, CPSC 572, CPSC 573, CPSC 585, ENAS 521, ENAS 541, ENAS 559, ENAS 606, ENAS 615, ENAS 703, ENAS 704, ENAS 708, ENAS 752, ENAS 755, ENAS 770, ENAS 773, ENAS 778, ENAS 787, ENAS 848, ENAS 850, ENAS 851, ENAS 902 (if not used to satisfy the math requirement), ENAS 994, PHYS 628. There is a math requirement that must be met by taking CPSC 553, 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 BENG 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 BENG 990, and maintain an average of at least High Pass.

Teaching Students are required to serve as a teaching fellow for 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. 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.

The Master's of Science in Personalized Medicine and Applied Engineering Directed and taught jointly by faculty in the School of Engineering & Applied Sciences and the School of Medicine, this program prepares biomedical, mechanical, and electrical engineers, as well as computer science majors and medical students, with the tools to develop innovative 3D solutions for personalized medicine. The program trains graduate students to develop and apply 3D technology to address surgical and medical conditions, with the goal of personalizing healthcare treatments to improve patient clinical outcomes. Additional societal benefits include lower healthcare costs and improved patient quality of life. Prospective students should apply through the Graduate School of Arts and Sciences (https://gsas.yale.edu/admissions/degree-program-application-process).

The program is one full year: summer through spring. Students are required to participate in an eight-week, summer clinical immersion session prior to registration in fall term sequence courses. Although course credit is not awarded for the clinical program, completion of the requirement will be noted on the transcript.

Students have flexibility in selecting the focus of their special investigation projects as well as an optional biomedical engineering industry collaboration project ("internal internship") tailored to their specific academic backgrounds and interests. For example, students with a strong engineering background may want to focus on medical school-focused classes, while medical students may want to focus on engineering-related courses. Students must take a total of eight courses, of which six courses are required of all students in the program: PMAE 526, PMAE 527, PMAE 528, PMAE 529, and two terms of PMAE 532 or PMAE 990. In rare exceptions, students may be allowed to take both with approval from the program director and DGS. With the approval of the program's DGS, the final two courses may be chosen from Yale-wide graduate-level technical electives, which must be approved by the program's DGS. An average grade of at least High Pass is required, with at least one grade of Honors.

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 and Environmental Engineering through the Graduate School of Arts and Sciences (https://gsas.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 information is available via email to engineering@yale.edu or at our 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.

CENG 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 500a, Mathematical Methods I Martin Pfaller
A beginning, graduate-level introduction to ordinary and partial differential equations, vector analysis, linear algebra, and complex functions. Laplace transform, series expansion, Fourier transform, and matrix methods are given particular attention. Applications to problems frequently encountered in engineering practice are stressed throughout.

ENAS 502b / S&DS 551b, Stochastic Processes Ilias Zadik
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 509a, Electronic Materials Mengxia Liu
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 Douglas Rothman and Ansel Hillmer
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 and Emma Carley
This full 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).

ENAS 518a / CBIO 635 / MB&B 635a, Quantitative Methods in Biophysics Nikhil Malvankar, Julien Berro, and Yong Xiong
An introduction to quantitative methods relevant to analysis and interpretation of biological data. Topics include statistical testing, data presentation, and error analysis; introduction to artificial intelligence-based data analysis tools, Alpha Fold Tutorial, introduction to mathematical modeling of biological dynamics; and Fourier analysis in signal/image processing and macromolecular structural studies. Instruction in basic programming skills and data analysis using MATLAB; study of real data from

MB&B research groups. Prerequisites: MATH 120 and MB&B 600 or equivalents, or permission of the instructors.

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

ENAS 521b, 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 canonical ensembles and the partition functions, fluctuations; Boltzmann statistics; Fermi-Dirac and Bose-Einstein statistics. Application to ideal monatomic and diatomic gases is covered.

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

ENAS 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 534a, Biomaterials Anjelica Gonzalez
Introduction to materials, classes of materials from atomic structure to physical properties. Major classes of materials: metals, ceramics and glasses, and polymers, addressing their specific characteristics, properties, and biological applications. Throughout the presentation of the synthesis, characterization, and properties of the classes of materials, a connection is made to the selection of materials for use in specific biological applications by matching the material's properties to those necessary for success in the application. Case studies address the successes and failures of particular materials from each of the classes in biological applications.

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

ENAS 539a, Small Objects Timothy Newton
This course is offered to graduate and undergraduate students who wish to pursue their own special talents, follow their passions, and expand possibilities and creative impulses to create a small object of their own design. The course is cross-listed with architecture, neuroscience, and engineering & applied science and intentionally brings together students with different backgrounds and experiences. The course explores the ideation, design processes, and fabrication of a functioning prototype. Potential areas of exploration include, but are not limited to: jewelry, furniture, experimental scientific instruments, electronic devices, architectural objects, lighting, cutlery, packaging, and musical instruments. Proposal submissions are due by August 18. See course syllabus for course and proposal details. Selection for the course is through application only.

ENAS 541a / CB&B 523a / MB&B 523a / PHYS 523a, Biological Physics Yimin Luo
This course has three aims: (1) to introduce students to the physics of biological systems, (2) to introduce students to the basics of scientific computing, and (3) to familiarize students with characterization methods and analysis tools. We focus on studies of a broad range of biophysical phenomena including diffusion, polymer statistics, entropic forces, membranes, and cell motion using computational tools and methods. We provide intensive tutorials for Matlab including basic syntax, arrays, functions, plotting, and importing and exporting data.

ENAS 542b, Topics in Computational and Systems Biology Purushottam Dixit
This course covers topics related to modeling biological networks across time and length scales. Specifically, the course covers models of intracellular signaling networks, transcriptional regulation networks, cellular metabolic networks, and ecological networks in microbial consortia. For each type of network, we cover the biological basics, standard mathematical treatments including deterministic and stochastic modeling, methods to infer model parameters from data, and new machine-learning based inference approaches. The required mathematical methods are briefly covered. The course assignments involve coding in MATLAB.

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

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

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

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

ENAS 558a, Introduction to Biomechanics Michael Murrell
An introduction to the biomechanics used in biosolid mechanics, biofluid mechanics, biothermomechanics, and biochemomechanics. Diverse aspects of 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
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 565a, Practical Applications of Bioimaging and Biosensing Daniel Coman, Ansel Hillmer, and Evelyn Lake
Detecting, measuring, and quantifying the structural and functional properties of tissue is of critical importance in both biomedical research and medicine. This course focuses on the practicalities of generating quantitative results from raw bioimaging and biosensing data to complement other courses focus on the theoretical foundations which enable the collection of these data. Participants in the course work with real, cutting-edge data collected here at Yale. They become familiar with an array of current software tools, denoising and processing techniques, and quantitative analysis methods that are used in the pursuit of extracting meaningful information from imaging data. The subject matter of this course ranges from bioenergetics, metabolic pathways, molecular processes, brain receptor kinetics, protein expression and interactions to wide spread functional networks, long-range connectivity, and organ-level brain organization. The course provides a unique hands-on experience with processing and analyzing *in vitro* and *in vivo* bioimaging and biosensing data that is relevant to current research topics. The specific imaging modes which are covered include *in vivo* magnetic resonance spectroscopy (MRS) and spectroscopic imaging (MRSI), functional, structural, and molecular imaging (MRI), wide-field fluorescent optical imaging, and positron emission tomography (PET). The course provides the necessary background in biochemistry, bioenergetics, and biophysics for students to motivate the image manipulations which they learn to perform. Prerequisites: Math through first order differential equations, PHYS 180/181, CHEM 161, BIOL 101/102, BENG 249 or other experience with scientific software like MATLAB, BENG 350 and BENG 410 (both of which can be taken at the same time as this course) 0 Course cr

ENAS 566b, Engineering of Drug Delivery W. Mark Saltzman
Drug delivery is a field of biomedical engineering that aims to develop approaches and technologies for getting pharmaceutical agents into particular cells and tissues in the body for a biological effect, while minimizing unwanted toxic or side effects. The course describes two interrelated fields of study: (1) mathematical descriptions of the biological barriers to drug delivery (diffusion, permeation through membranes, lifetime of circulation); and (2) engineering design to improve drug delivery. Prerequisite: ENAS 551a.

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 570b / C&MP 560b / MCDB 560b / PHAR 560b, Cellular and Molecular Physiology: Molecular Machines in Human Disease Emile Boulpaep and Peter Takizawa
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 / INP 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 / INP 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 591a / QMSE 501a, Introduction to Quantum Materials Science and Engineering Sohrab Ismail-Beigi and Corey O'Hern
This course introduces basic concepts and methodologies relevant for understanding and performing research on quantum materials. The course is designed for Ph.D. students in engineering, physics, chemistry, mathematics, or computer science who are interested in the promise of quantum materials and who wish to understand what quantum materials are, how they can be used, and how one investigates them scientifically and engineers their properties. The emphasis is on core concepts and learning by solving research relevant problems on model systems via computer simulations and theoretical analyses. Note that this course is required for the QMSE certificate. Prerequisites: one semester of quantum mechanics at the undergraduate level and one semester of undergraduate level vector calculus and differential equations.

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

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

ENAS 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 606a, 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 609a, Principles and Design of Energy Devices Shu Hu
This is a comprehensive course with content at the intersection of nanoscale science, engineering, and technology, including application areas and nanofabrication technique. Topics include nanoscaled photovoltaic cells, hydrogen storage, fuel cells, and nanoelectronics; layer-by-layer assembly; organic-inorganic mesostructures; colloidal crystals, organic monolayers, proteins, DNA and abalone shells; synthesis of carbon nanotubes, nanowire, and nanocrystals; microelectromechanical systems (MEMs) devices; photolithography, electron beam lithography, and scanning probe lithography; lithium-based batteries; and nanomanufacturing (roll to roll, nanoimprint lithography, inkjet printing).

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

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

ENAS 642b, Environmental Physicochemical Processes Jaehong Kim
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 648b, 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 660b, Green Engineering and Sustainability Julie Zimmerman
This hands-on course highlights the key approaches to advancing sustainability through engineering design. The class begins with discussions on sustainability, metrics, general design processes, and challenges to sustainability. The current

approach to design, manufacturing, and disposal is discussed in the context of examples and case studies from various sectors. This provides a basis for what and how to consider when designing products, processes, and systems to contribute to furthering sustainability. The fundamental engineering design topics to be addressed include toxicity and benign alternatives, pollution prevention and source reduction, separations and disassembly, material and energy efficiencies and flows, systems analysis, biomimicry, and life cycle design, management, and analysis. Students tackle current engineering and product design challenges in a series of class exercises and a final design project.

ENAS 670b, Membrane Science and Technology Menachem Elimelech
This course provides a comprehensive introduction to membrane science and technology, covering principles, theories, applications, and advancements in membrane-based separation processes. Topics include overview of membrane technologies, membrane materials, solvent and solute transport mechanisms and theories, and applications in chemical separations, water treatment, desalination, and energy. Students also explore emerging trends in membrane research and applications.

ENAS 700a or b, 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 Cong Su
Survey of nanomaterial synthesis methods and current nanotechnologies. Approaches to synthesizing nanomaterials; characterization techniques; device applications that involve nanoscale effects.

ENAS 704b, Theoretical Fluid Dynamics Juan 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, BioMEMS & Biomedical Microdevices 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 713a, Acoustics Eric Dieckman
Wave propagation in strings, membranes, plates, ducts, and volumes; plane, cylindrical, and spherical waves; reflection, transmission, and absorption characteristics; sources of sound. Introduction to special topics such as architectural, underwater, psychological, nonlinear, and musical acoustics, noise, and ultrasonics.

ENAS 718b, Advanced Electronic Devices Mengxia Liu
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 725a / APHY 725a, 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 747b, Applied Numerical Methods for Algebraic Systems, Eigensystems, and Function Approximation Beth Anne Bennett
The derivation, analysis, and implementation of various numerical methods. Topics include root-finding methods, numerical solution of systems of linear and nonlinear equations, eigenvalue/eigenvector approximation, polynomial-based interpolation, and numerical integration. Additional topics such as computational cost, error analysis, and convergence are studied in several contexts throughout the course.

ENAS 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 770b, Introduction to Soft Robotics Rebecca Kramer-Bottiglio
This course covers topics including robot kinematics, elastic materials models, conductive composites, responsive material actuators, simple controllers, and physics-based soft robot simulation. The course also includes a project. Projects must involve theoretical modeling, design implementation, and/or experimental testing of a scientific hypothesis, and must have a mechanics and/or materials component. Prerequisites: prior course work in solid mechanics and familiarity with MATLAB.

ENAS 772b, Introduction to Embedded Robotic Systems Ahalya Prabhakar
This project-based course gives students an introduction to concepts useful for a robotics engineer working with practical embedded systems as well as experience with a variety of sensors and software tools needed for working with robots. Students are provided an overview of the different components of robotic systems, including planning, estimation, and control. Topics such as kinematics, dynamics (for robotics), frame transforms, twists, and wrenches will be introduced in the course. In addition,

students learn how to use the Robot Operating System (ROS 2) to connect concepts and components relevant to robotic systems. Furthermore, they learn how to write software and simulations to interface sensors and actuators, and to integrate different components in a system, including planning, estimation, and control. By the end of the course, students complete a project using a real robot.

ENAS 776a, Fluid Mechanics of Natural Phenomena Amir Pahlavan
This course draws inspiration from nature and focuses on utilizing the fundamental concepts of fluid mechanics and soft matter physics to explain these phenomena. We study a broad range of problems related to (1) nutrient transport in plants, slime molds, and fungi and the adaptation of their networks in dynamic environments, (2) collective behavior and chemotaxis of swimming microorganisms, and (3) pattern formation in nature, e.g. icicles, mud cracks, salt polygons, dendritic crystals, and Turing patterns. We also discuss how our understanding of these problems could be used to develop sustainable solutions for the society, e.g. designing synthetic trees to convert CO_2 to oxygen, developing micro/nano robots for biomedical applications, and utilizing pattern formation and self-assembly to make new materials.

ENAS 778a, Advanced Robotic Mechanisms Aaron Dollar

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 800a, Smart City Engineering with IoT Andrei Khurshudov
A smart city is one that employs technology to gather data from various sources such as sensors, people, devices, vehicles, and buildings. This data is then used for optimal decision-making and control. Cities around the world are adopting "smart" technology, thereby transforming urban life. Utilizing the Internet of Things (IoT), cities like Barcelona, London, and Singapore aim to improve living standards, boost the economy, and enhance sustainability. They achieve this through innovations like intelligent streetlights, smart electric grids, and advanced traffic systems. The Internet of Things, a global network consisting of connected sensors, machines, devices, communication networks, and decision-making algorithms is facilitating a new wave of the industrial revolution. This course is designed for *both graduate and undergraduate students* and offers a comprehensive overview of the key technologies shaping contemporary and future smart cities. It delves into the foundational elements of IoT devices and applications, covering topics such as: data analytics using ML and AI (which will be used to address practical problems); smart sensors and interconnected devices; IoT data: formats, transmission, and storage; Cloud and Edge computing, and the associated trade-offs; connectivity and wireless communication technologies; device failure prevention and reliability modeling; and other relevant subjects.

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

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

ENAS 820b / CPSC 520b, Computer Architecture Staff
This course offers a treatment of computer architectures for high-performance and power/energy-efficient computer systems. Topics include the foundations of general-purpose computing, including instruction set architectures, pipelines, superscalar and out-of-order execution, speculation, support for precise exceptions, and simultaneous multi-threading. We also cover domain-specific hardware (e.g., graphics processing units), and ongoing industry efforts to elevate them to the status of first-class computing units. In tandem, we cover topics relevant to both general-purpose and domain-specific computing, including memory hierarchies, address translation and virtual memory, on-chip networks, machine learning techniques for resource management, and coherence techniques. If time permits, we study the basics of emerging non-classical computing paradigms like neuromorphic computing. Overall, this course offers insights on how the computing industry is combating the waning of traditional technology scaling via acceleration and heterogeneity. Prerequisites: Courses similar to CPSC 323, 223, and 202. This is a programming-intensive course, so comfort with large programming projects is essential.

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

ENAS 850a / APHY 548a / PHYS 548a, Solid State Physics I Vidvuds Ozolins
A two-term sequence (with APHY 549) 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 Yu He
A two-term sequence (with APHY 548) 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 868a, Emerging Materials and Technologies toward Sustainability Liangbing Hu
The goal of this course is to demonstrate the role of new materials and emerging technologies in solving one of the most critical socio-economic issues of our time —sustainability. The course focuses on electrochemical, electrical, optical, thermal, and mechanically functional materials and their use in energy devices. Topics to be covered include electrochemical energy conversion and storage (fuel cells and batteries), catalysts and membrane separations (fossil fuel and biomass energy conversion), electrified heating (Joule, plasma, microwave), solar thermal and fuel, thermoelectrics, energy efficient lighting, and building energy savings (light, thermal).

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 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 905a, Applied Digital Signal Process Roman Kuc

ENAS 924b, Computer Hardware Security Jakub Szefer
This course provides an in-depth examination of computers and their hardware-based security issues. The operation of the hardware, from transistors to processor microarchitectures, has intimate impact on the security of the whole system. Often, software or algorithms executing on a computer have no control over, or detailed access to, the underlying hardware. Yet, the operation of the hardware and different types of side-effects, such as changing timing, changing power consumption, EM emanations, or different types of crosstalk effects lead to information leakage. To understand the hardware-based security issues, and how to prevent them, the course focuses on classical microprocessors, accelerators such as Field Programmable Gate Arrays, as well as emerging technologies such as Quantum Computers. For the different types of computers, the course teaches students about the various hardware security issues, and students are able to experiment and perform hands-on exercises to demonstrate different types of information leaks. Students also learn about latest research through reading and presenting research papers in class.

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 952a, Internet Engineering Leandros Tassiulas

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

ENAS 968a, Cloud Computing with FPGAs Jakub Szefer
This course is an intermediate- to advanced-level course focusing on digital design and use of Field Programmable Gate Arrays (FPGAs). The course centers around the new cloud computing paradigm of using FPGAs that 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). In the course, 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 learn about topics ranging from high-level ideas about cloud computing to low-level details of interfacing servers to FPGAs, PCIe protocol, AXI protocol, and other common communication protocols between hardware modules or between AXI protocols, and how to write software that runs on the cloud servers and leverages the FPGAs and the host computer, including Serial, SPI, and I2C. Students also learn about and use FPGA tools from Xilinx, but course also touches on tools available from Intel (formerly Altera) as well as open-source tools. The practical aspects of the course include semester-long projects leveraging commercial or in-lab remote FPGAs, based on the project selected by students. Students should be familiar with digital design basics and have some experience with Hardware Description Languages such as Verilog or VHDL.

ENAS 991a / MB&B 591a / MCDB 591a / PHYS 991a, Integrated Workshop Yimin Luo
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 Ian Abraham
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, and PID control.