MECHANICAL ENGINEERING

Co-directors of undergraduate studies: Beth Anne Bennett (beth.bennett@yale.edu), Becton 207, 432-0171, and Alessandro Gomez (alessandro.gomez@yale.edu), Mason M4, 432-4384; seas.yale.edu/departments/mechanical-engineering-and-materials-science

Mechanical engineering is among the most diversified of the traditional engineering disciplines. The mechanical engineer builds machines to extend our physical and mental capabilities and to convert traditional and novel energy sources into useful forms.

The role of the mechanical engineer has changed dramatically over the past few decades with the extensive use of high-performance computing and machine learning (in such areas as computational fluid dynamics, materials design, control, and manufacturing), the interfacing of microelectromechanical systems and actuators via microprocessors to build high-precision sensors and devices, and the advent of advanced materials (e.g., composites, shape-memory alloys, ceramics, and superconductors) for new applications (e.g., coatings, biomaterials, and computer storage). These areas offer mechanical engineering students special opportunities for creativity, demanding that they learn not only in depth but also in breadth. Demands for increased energy efficiency and reduced environmental impact—as might be realized, for example, in novel gas turbine or electric hybrid vehicles—require that students understand the fundamentals of mechanics, thermodynamics, fluid mechanics, combustion, and materials science. In all these tasks, the utmost consideration of the modern mechanical engineer is improving the quality of human life. The engineer must also be constantly aware of the finiteness of Earth's resources and its environment and of the burden that engineering places on them.

The educational mission of the Mechanical Engineering Program is to provide an excellent education, within one of the finest liberal arts universities in the nation, so that our students are prepared to become the next generation of mechanical engineers. Our students will have the ability to pursue graduate studies in Mechanical Engineering and pursue job opportunities as mechanical engineers in industry, government, and other sectors. To implement this mission, the following three educational objectives have been established for the Mechanical Engineering Program. First, graduates will have the scientific and technical background, engineering skills in analysis, design, and synthesis, as well as strong abilities in communication, teamwork, and critical thinking, to succeed and take on leadership roles in industry, government, and academia. Second, graduates will have a strong awareness and understanding of the impacts of engineering solutions on society and the environment, which will guide their professional and ethical decision-making processes. Third, graduates will be equipped to pursue postgraduate studies at top-tier programs in mechanical engineering and related fields.

Upon graduation, Yale's Mechanical Engineering students are expected to have achieved "Student Outcomes" as defined by ABET (www.abet.org) and the program. The Mechanical Engineering major produces graduates who demonstrate: (1) an ability to identify, formulate, and solve complex engineering problems by applying principles

of engineering, science, and mathematics; (2) an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors; (3) an ability to communicate effectively with a range of audiences; (4) an ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts; (5) an ability to function electively on a team whose members together provide leadership, create a collaborative environment, establish goals, plan tasks, and meet objectives; (6) an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions; and (7) an ability to acquire and apply new knowledge as needed, using appropriate learning strategies.

COURSES FOR NONMAJORS

Mechanics and mechanical engineering content can be found in several courses intended for those not majoring in science. See Engineering and Applied Science.

THE MECHANICAL ENGINEERING PROGRAM

At Yale, three mechanical engineering programs are offered: a B.S. degree program with a major in Mechanical Engineering, a B.S. degree program with a major in Engineering Sciences (Mechanical), and a B.A. degree program with a major in Engineering Sciences (Mechanical). Prospective majors in both B.S. programs are advised to complete introductory physics and mathematics through calculus (MATH 1150) by the end of their first year.

A student's undergraduate engineering program may include one or more special project courses MENG 4991 or MENG 4992 (at most one of which may count toward major requirements) in which the student pursues a particular research interest through design-oriented projects and experimental investigations. Projects may be initiated by the student, may be performed in a team, or may be derived from the ideas of faculty members who place undergraduates in their ongoing research projects. All interested students should contact the director of undergraduate studies (DUS) for more information on special project courses.

B.S. degree program in Mechanical Engineering This is the most technically intensive mechanical engineering degree program and is accredited by the Engineering Accreditation Commission of ABET, Inc. This program is appropriate for students who plan careers as practicing engineers in industry, consulting firms, or government, as well as for students who are considering a career in research and plan to pursue an advanced degree in engineering.

B.S. degree program in Engineering Sciences (Mechanical) This non-ABET degree program is suitable for students who wish to gain significant expertise within mechanical engineering while combining their engineering studies with related disciplines. For example, a number of students have taken courses in architecture while pursuing a program in mechanical engineering that emphasizes structural mechanics; similarly, a student with an interest in computer graphics might combine engineering courses in computer-aided design with programming courses from the Department of Computer Science.

B.A. degree program in Engineering Sciences (Mechanical) In a society with increasing levels of technical sophistication, a well-rounded individual must have some background in science and technology. The non-ABET B.A. program is designed for students who may be planning careers in business, law, economics, medicine, journalism, or politics but need to understand the impact that science and technology can have on society at large. An understanding of engineering methods and practices, combined with a traditional liberal arts education, provides a strong background for a variety of careers. The program is well-suited for students who wish to fulfill the requirements of two majors.

The major for all three degree programs requires a group of prerequisites or equivalents; several courses beyond the prerequisites; and a senior requirement, as indicated below.

PREREQUISITES

B.S. degree program in Mechanical Engineering The prerequisites in mathematics are MATH 1120, MATH 1150, and ENAS 1510, or equivalent. The basic science prerequisites are one physics lecture from PHYS 1800, PHYS 2000, or PHYS 2600, and one from PHYS 1810, PHYS 2010, or PHYS 2610, or equivalents; one laboratory from PHYS 1650L or PHYS 2050L, and one from PHYS 1660L or PHYS 2060L, or equivalents; and one 1-credit lecture course in chemistry, numbered CHEM 1610 or higher, or equivalent. The chemistry lecture course may be waived for a Chemistry AP score of 4 or 5 or an IB Higher level or Standard level score of 6 or 7.

B.S. degree program in Engineering Sciences (Mechanical) The prerequisites in mathematics are MATH 1120, MATH 1150, and ENAS 1510, or equivalent. The basic science prerequisites are one physics lecture from PHYS 1800, PHYS 2000, or PHYS 2600, and one from PHYS 1810, PHYS 2010, or PHYS 2610, or equivalents; one laboratory from PHYS 1650L or PHYS 2050L, and one from PHYS 1660L, PHYS 2060L, or MENG 2616L.

B.A. degree program in Engineering Sciences (Mechanical) The prerequisites in mathematics are MATH 1120 and MATH 1150. The basic science prerequisite is physics at least to the level of PHYS 1700, PHYS 1710.

REQUIREMENTS OF THE MAJOR

See Links to the attributes indicating courses approved for the Mechanical Engineering major requirements.

B.S. degree program in Mechanical Engineering requires twenty courses for 19.5 credits beyond the prerequisites as follows:

1. Advanced mathematics: ENAS 1940 and MATH 2220 or MATH 2250

2. Mechanical engineering and related: MENG 1105, 2311, 2511, 2615, 2616L, 3020L, 3125, 3323, 3422, 3423L, 3424, 4137L and 4138L (the senior requirement), ENAS 1300, ECE 2000

3. Technical electives: three approved technical electives chosen in consultation with the DUS; at most one course from MENG 4991 or MENG 4992 may be counted as one of the three technical electives.

The curriculum in this program is arranged in prescribed patterns, but some departures from it are possible with approval of the DUS.

B.S. degree program in Engineering Sciences (Mechanical) The major requires twelve approved course credits in engineering (with at most one course from MENG 4991 or MENG 4992), beyond the prerequisites and including the senior project, which can cover a broad array of topics within the subject, provided that they contribute to a coherent program. Students should consult with the DUS at the beginning of their sophomore year.

B.A. degree program in Engineering Sciences (Mechanical) The program requires eight approved course credits in engineering (with at most one course from MENG 4991 or MENG 4992), beyond the prerequisites and including the senior project. Students should consult with the DUS at the beginning of their sophomore year.

Credit/D/Fail No course taken Credit/D/Fail may be applied toward the requirements of the major, including prerequisites.

Outside credit Courses taken at another institution or during an approved summer or term-time study abroad program may count toward the major requirements with DUS approval.

SENIOR REQUIREMENT

B.S. degree program in Mechanical Engineering Students satisfy the senior requirement by taking MENG 4137L (full credit) and MENG 4138L (half credit) in the senior year.

B.S. degree program in Engineering Sciences (Mechanical) Students satisfy the senior project requirement by completing MENG 4154; MENG 4991 or 4992; or another upper-level design course (taken during the senior year) chosen in consultation with the DUS. Only one Special Projects Course (MENG 4991 or 4992) may be counted toward the requirements of the major.

B.A. degree program in Engineering Sciences (Mechanical) Students satisfy the senior project requirement by completing MENG 4991 or 4992; or another upper-level design course (taken during their senior year) chosen in consultation with the DUS. Only one Special Projects Course (MENG 4991 or 4992) may be counted toward the requirements of the major.

SUMMARY OF MAJOR REQUIREMENTS

MECHANICAL ENGINEERING, B.S.

Prerequisites MATH 1120, MATH 1150, and ENAS 1510, or equivalent; 2 physics lecture courses (1 from PHYS 1800, PHYS 2000, or PHYS 2600; 1 from PHYS 1810, PHYS 2010, or PHYS 2610, or equivalents) and 2 labs (1 from PHYS 1650L or PHYS 2050L; 1 from PHYS 1660L or PHYS 2060L, or equivalents), and 1 1.0-credit chemistry lecture course numbered CHEM 1610 or higher, or equivalent

Number of courses 20 courses and 19.5 credits beyond prerequisites (including senior req)

Specific courses required ENAS 1300 and 1940; ECE 2000; MATH 2220 or 2250; MENG 1105, 2311, 2511, 2615, 2616L, 3020L, 3125, 3323, 3422, 3423L, 3424
Distribution of courses 3 technical electives chosen in consultation with DUS (at most one of MENG 4991 or MENG 4992)
Substitution permitted With DUS approval
Senior requirement MENG 4137L and MENG 4138L taken in senior year

ENGINEERING SCIENCES (MECHANICAL), B.S.
Prerequisites MATH 1120, MATH 1150, and ENAS 1510, or equivalent; 2 physics lecture courses (1 from PHYS 1800, PHYS 2000, or PHYS 2600; 1 from PHYS 1810, PHYS 2010, or PHYS 2610, or equivalents) and 2 labs (1 from PHYS 1650L or PHYS 2050L; 1 from PHYS 1660L, PHYS 2060L, or MENG 2616L)
Number of courses 12 course credits beyond prerequisites (incl senior req)
Substitution permitted With DUS approval
Senior requirement MENG 4154; MENG 4991 or 4992; or another upper-level design course chosen in consultation with the DUS

ENGINEERING SCIENCES (MECHANICAL), B.A.
Prerequisites MATH 1120, MATH 1150; PHYS 1700, PHYS 1710 or higher
Number of courses 8 course credits beyond prerequisites (incl senior req)
Substitution permitted With DUS approval
Senior requirement MENG 4991 or 4992; or another upper-level design course chosen in consultation with the DUS

Courses

MENG 1105a or b, Mechanical Design Omer Subasi
A course designed for potential majors in mechanical engineering, with units on design methodology, statics, mechanics of materials, and machining. Includes a design project. Enrollment is typically limited to first-years and sophomores; other interested Mechanical Engineering students should take MENG 2147 instead. Prerequisite: physics at the level of PHYS 1800, or permission of instructor. SC 0 Course cr

MENG 2050a or b, Computer-Aided Engineering Omer Subasi
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. Prerequisite: ENAS 1300 or permission of instructor. QR

MENG 2147b, Intermediate Mechanical Design Omer Subasi
This is a hands-on, project-based course in mechanical design and mechatronic systems. Students design, analyze, fabricate, and control a linkage-based walking robot, progressing from mechanical fundamentals to integrated electromechanical systems. The course focuses on core mechanical design topics, including computer-aided design (CAD), parametric modeling, linkage kinematics and force analysis, material selection, failure and stress analysis, and the design of mechanical elements. Students fabricate components using modern manufacturing techniques such as water-jet cutting, laser cutting, CNC machining, and additive manufacturing. In addition, there will be emphasis on system integration, including motor selection, drivetrain design, electronics integration, and embedded control. Students work with motors,

motor drivers, sensors, and microcontrollers, and develop basic motor control and Arduino-based interfaces to actuate and control their robots. Throughout the semester, students apply engineering theory to a design problem while developing practical skills in manufacturing, prototyping, and debugging. The course culminates in a fully functional walking robot and a comprehensive design portfolio documenting the mechanical design, analysis, fabrication process, and control strategy. Prerequisite: MENG 1105.

MENG 2311a, Mechanical Engineering I: Strength and Deformation of Mechanical Elements Yimin Luo
Elements of statics; mechanical behavior of materials; equilibrium equations, strains and displacements, and stress-strain relations. Elementary applications to trusses, bending of beams, pressure vessels, and torsion of bars. Prerequisites: PHYS 1800, 2000, or 2600, and MATH 1150. QR, SC RP

MENG 2511a or b, Thermodynamics for Mechanical Engineers Alessandro Gomez
Study of energy and its transformation and utilization. First and Second Laws for closed and open systems, equations of state, multicomponent nonreacting systems, auxiliary functions (H, A, G), and the chemical potential and conditions of equilibrium. Engineering devices such as power and refrigeration systems and their efficiencies. Prerequisites: PHYS 1800, 2000, or 2600, and MATH 1150. QR, SC

MENG 2615a or b, Introduction to Materials Science Jan Schroers
Study of the atomic and microscopic origin of the properties of engineering materials: metals, glasses, polymers, ceramics, and composites. Phase diagrams; diffusion; rates of reaction; mechanisms of deformation, fracture, and strengthening; thermal and electrical conduction. Prerequisites: elementary calculus and background in basic mechanics (deformation, Hooke's law) and structure of atoms (orbitals, periodic table). QR, SC RP

MENG 2616La or b, Solid Mechanics and Materials Science Laboratory Cong Su
This course introduces undergraduate students to a variety of microstructure characterization and mechanical testing techniques for engineering materials. It offers hands-on laboratory projects that enable students to investigate the relationship between the mechanical behavior of materials and their microstructure. Topics include bending and hardness tests, processing of materials, and fracture. The course uses several characterization methods, including scanning electron microscopy, atomic force microscopy, x-ray diffraction, differential scanning calorimetry, nanomechanical testing, and tensile testing. Prerequisite: MENG 2615 SC RP 0 Course cr

MENG 3020Lb, Mechatronics Laboratory Madhusudhan Venkadesan
Hands-on synthesis of control systems, electrical engineering, and mechanical engineering. Review of Laplace transforms, transfer functions, software tools for solving ODEs. Review of electronic components and introduction to electronic instrumentation. Introduction to sensors; mechanical power transmission elements; programming microcontrollers; PID control. Prerequisites: MATH 2220 or equivalent, ENAS 1940 or equivalent, ENAS 1300, and ECE 2000; or permission of instructor. QR RP

* **MENG 3125a, Machine Elements and Manufacturing Processes** Edward Diehl
This course provides students a working knowledge of two fundamental topics related to mechanical design: machine elements and manufacturing processes. *Machine*

elements refer one or more of a range of common design elements that transmit power and enable smooth and efficient motion in mechanical systems with moving parts. This course introduces the most common of these elements and gives students the tools to systems design with them. Topics include common linkages, gearing, bearings, springs, clutches, brakes, and common actuators such as DC motors. *Manufacturing processes* are necessary for the mechanical design engineer to effectively perform her or his duties; they provide an understanding of how the parts and systems that they design are fabricated, allowing "Design for Manufacturing" principles to be taken into account in the product development process. Students learn the basics of common commercial manufacturing processes for mechanical systems, including low-volume processes such as machining to high-volume processes such as casting (metal parts), molding (plastic parts), and stamping (sheet metal parts). Prerequisites: MENG 2311. MENG 1105 and CAD experience are recommended.

MENG 3323a or b, Mechanical Engineering III: Dynamics Mark Orelup
Kinematics and dynamics of particles and systems of particles. Relative motion; systems with constraints. Rigid body mechanics; gyroscopes. Prerequisites: PHYS 1800 or 2000, and MATH 1200 or ENAS 1510. QR, SC

MENG 3422a or b, Mechanical Engineering II: Fluid Mechanics Mitchell Smooke
Mechanical properties of fluids, kinematics, Navier-Stokes equations, boundary conditions, hydrostatics, Euler's equations, Bernoulli's equation and applications, momentum theorems and control volume analysis, dimensional analysis and similitude, pipe flow, turbulence, concepts from boundary layer theory, elements of potential flow. Prerequisites: ENAS 1940 or equivalent, and physics at least at the level of PHYS 1800. QR, SC RP

* **MENG 3423Lb, Fluid Mechanics and Thermodynamics Laboratory** Bauyrzhan Primkulov
Hands-on experience in applying the principles of fluid mechanics and thermodynamics. Integration of experiment, theory, and simulation to reflect real-world phenomena. Students design and test prototype devices. Prerequisites: MENG 2511 and 3422. WR, SC 0 Course cr

MENG 3424b, Mechanical Engineering IV: Fluid and Thermal Energy Science Beth Anne Bennett
Fundamentals of mechanical engineering applicable to the calculation of energy and power requirements, as well as transport of heat by conduction, convection, and radiation. Prerequisites: MENG 2511, 3422, and ENAS 1940; or permission of instructor. QR, SC

MENG 3675b, Thermodynamics, Kinetics, and Structure of Materials Jan Schroers
This advanced-level course focuses on the thermodynamic and kinetic aspects of materials and how they define structure and properties. We first discuss thermodynamics relevant to materials. This includes thermodynamic laws, auxiliary functions to develop convenient equations of state to describe equilibrium, Gibbs Free Energy (G), experimental determination of G, model calculations of G such as ideal solutions and regular solutions, using G curves to construct equilibrium conditions, phase diagram constructions, reading of phase diagrams. We then focus on solidification which we develop from the phenomena of undercooling, nucleation and growth. Combining both, allows us to predict microstructures formed during

solidification far and close to equilibrium. We also discuss glass formation, the case when nucleation and growth can be suppressed, and the liquid freezes upon cooling into a glass. Prerequisite: MENG 2615. o Course cr

MENG 4040b / ENAS 4040b, 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. Prerequisites: MATH 1150, and 2220 or 2250, or equivalents; ENAS 1300 or some experience with Matlab, C++, or Fortran. QR

MENG 4137La, Mechanical Design: Process and Implementation I Edward Diehl
This course is the first half of the capstone design sequence (students take MENG 4138L in the spring semester of the same academic year) and is a unique opportunity to apply and demonstrate broad and detailed knowledge of engineering in a team effort to design, construct, and test a functioning engineering system. The lecture portion of the class provides guidance in planning and managing your project, as well other topics associated with engineering design. This course sequence requires quality design; analyses and experiments to support the design effort; and the fabrication and testing of the engineered system; as well as proper documentation and presentation of results to a technical audience. Prerequisites: MENG 2311, 3125, and 3422. MENG 1105 and 3020L are strongly suggested. RP

MENG 4138Lb, Mechanical Design: Process and Implementation II Edward Diehl
This course is the second half of the capstone design sequence (students take MENG 4137L in the fall semester of the same academic year) and is a unique opportunity to apply and demonstrate broad and detailed knowledge of engineering in a team effort to design, construct, and test a functioning engineering system. The lecture portion of the class provides guidance in planning and managing your project, as well other topics associated with engineering design. This course sequence requires quality design; analyses and experiments to support the design effort; and the fabrication and testing of the engineered system; as well as proper documentation and presentation of results to a technical audience. Prerequisites: MENG 2311, 3125, 3422, and 4137L. MENG 1105 and 3020L are strongly suggested. ½ Course cr

MENG 4145b, Advanced Design and Analysis of Machines Edward Diehl
There are many useful, classic mechanisms that require a single actuator to operate. These include four-bar mechanisms, slider-cranks, and cam-followers. In this course, students learn to design (synthesize) and analyze the kinematics and kinetics of classic machines. This course focuses on planar systems, and students learn to write and solve the equations of motion of complex linkages. Students design and analyze using SolidWorks and solve equations with MATLAB. Projects are designed, analyzed, built, and tested, and their results are compared to the analytical and simulated answers. Prerequisites: ENAS 1300, MENG 3125.

MENG 4154b / BENG 4104b, Medical Device Design and Innovation Daniel Wiznia and Steven Tommasini

The engineering design, project planning, prototype creation, and fabrication processes for medical devices that improve patient conditions, experiences, and outcomes. Students develop viable solutions and professional-level working prototypes to address clinical needs identified by practicing physicians. Some attention to topics such as intellectual property, the history of medical devices, documentation and reporting, and regulatory affairs. o Course cr

* **MENG 4359a / BENG 4559a, Neuromuscular Biomechanics** Madhusudhan Venkadesan

Mechanics and control of animal movement, including skeletal muscle mechanics, systems-level neural and sensory physiology, elements of feedback control, and optimal control. Deriving equations of motion for multibody mechanical systems that are actuated by muscles or muscle-like motors; incorporating sensory feedback; analyzing system properties such as stability and energetics. Prerequisites: MENG 3323 and MATH 2220 or equivalents, and familiarity with MATLAB or a similar scientific computing environment. QR RP

MENG 4370b / BENG 4570b, Computational Mechanics Martin Pfaller

This course integrates fundamental concepts from nonlinear continuum mechanics and finite element methods applied to solid and fluid mechanics, focusing on theoretical understanding and numerical techniques. Topics covered are fundamentals of tensor calculus, kinematics, balance equations, constitutive relationships, geometric and material nonlinearities, nonlinear solution strategies, stability, nonlinear dynamics, errors, convergence, and adaptivity. Applications in biomedical engineering are stressed throughout the course. Fundamentals in calculus, differential equations, and linear algebra.

MENG 4441a / AMTH 4441a / APHY 4410a / PHYS 4441a, Nonlinear Dynamics Bauyrzhan Primkulov

This course introduces nonlinear dynamics and chaos in dissipative systems, tailored broadly for undergraduate students in science and engineering. It focuses on simple dynamical models, the mathematical principles underlying their behaviors, their connection to natural phenomena, and techniques for data analysis and interpretation. Key topics include forced and parametric oscillators, phase space analysis, periodic, quasiperiodic, and aperiodic flows, sensitivity to initial conditions, and strange attractors such as the Lorenz attractor. The course also explores phenomena like period doubling, intermittency, and quasiperiodicity, emphasizing nonlinear processes describable by a limited number of time-evolving variables. ENAS 1510 (Multivariable Calculus or equivalent), ENAS 1940 (Differential Equations or equivalent) SC

* **MENG 4469a, Aerodynamics** Jesse Tinajero

Review of fluid dynamics. Inviscid flows over airfoils; finite wing theory; viscous effects and boundary layer theory. Compressible aerodynamics: normal and oblique shock waves and expansion waves. Linearized compressible flows. Some basic knowledge of thermodynamics is expected. Prerequisite: MENG 3422 or permission of instructor. QR, SC

MENG 4664b, 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. Some knowledge of basic physics, mathematics, chemistry, and thermodynamics is expected. SC 0 Course cr

MENG 4672b, Electronic and Optical Properties of Energy Materials Diana Qiu
This class explores the electronic and optical properties of materials from the perspective of electronic and molecular structure with a special focus on the microscopic origin and design of properties of interest for energy harvesting, storage, and transport. The course starts by briefly introducing concepts in quantum mechanics, such as wavefunctions and the time-independent Schrodinger equations. Then, we explore electronic structure in the context of designing materials for energy harvesting and generation, such as photovoltaics, thermoelectrics, and piezoelectrics. We also study dynamical processes, such as hot electron relaxation, multi-exciton generation, charge transport, and energy transport at a phenomenological level. Finally, we overview common energy storage materials, with a focus on solid-state batteries and solar fuels. Prerequisite: MENG 2615, ENAS 1510, or permission of instructor QR, SC

MENG 4673a, 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. Prerequisites: ENAS 1940 and MENG 2615, or permission of instructor. SC

* **MENG 4774a / BENG 4724a, 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. Prerequisite: MATH 120 or ENAS 151.

* **MENG 4850a / APHY 4500a / ENAS 450 / ENAS 4500a, Advanced Synchrotron Techniques and Electron Spectroscopy of Materials** Charles Ahn
Introduction to concepts of advanced x-ray and electron-based techniques used for understanding the electronic, structural, and chemical behavior of materials. Students learn from world-leading experts on fundamentals and practical applications of various diffraction, spectroscopy, and microscopy methods. Course highlights the use of synchrotrons in practical experiments. Prerequisites: physics and quantum

mechanics/physical chemistry courses for physical science and engineering majors, or by permission of instructor. QR, SC

* **MENG 4991a or b, Special Projects I** Omer Subasi
Faculty-supervised one- or two-person projects with emphasis on research (experiment, simulation, or theory), engineering design, or tutorial study. Students are expected to consult the course instructor, director of undergraduate studies, and/or appropriate faculty members to discuss ideas and suggestions for topics. Focus on development of professional skills such as writing abstracts, prospectuses, and technical reports as well as good practices for preparing posters and delivering presentations. Permission of advisor and director of undergraduate studies is required. Students are required to attend a 75-minute section once per week.

* **MENG 4992a or b, Special Projects II** Omer Subasi
Faculty-supervised one- or two-person projects with emphasis on research (experiment, simulation, or theory), engineering design, or tutorial study. Students are expected to consult the course instructor, director of undergraduate studies, and/or appropriate faculty members to discuss ideas and suggestions for topics. These courses may be taken at any time during the student's career and may be taken more than once. Prerequisites: MENG 4991; permission of adviser and Director of Undergraduate Studies.