ELECTRICAL ENGINEERING

Director of undergraduate studies: Fengnian Xia (fengnian.xia@yale.edu); seas.yale.edu/departments/electrical-engineering

Electrical Engineering broadly encompasses disciplines such as microelectronics, photonics, computer engineering, signal processing, control systems, and communications. Three electrical engineering degree programs are offered, as well as a joint degree between the electrical engineering and computer science departments.

1. The B.S. in Electrical Engineering, accredited by the Engineering Accreditation Commission of ABET, Inc., is the flagship degree program and is the most challenging program in electrical engineering. This program is appropriate for highly motivated students who are interested in entering the engineering profession, and who wish for a flexible enough program to consider a variety of other career paths.

Upon graduation, Yale’s B.S. Electrical Engineering (ABET) students are expected to achieve “student outcomes” as defined by ABET and the program. The Electrical 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 effectively on a team whose members together provide leadership, create a collaborative and inclusive 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; (7) an ability to acquire and apply new knowledge as needed, using appropriate learning strategies.

2. The B.S. in Engineering Sciences (Electrical) provides similar technical exposure and equivalent rigor as the ABET program, while retaining the flexibility for students to take a broader range of courses than those mandated by the ABET curriculum. The B.S. in Engineering Sciences (Electrical) is suitable for careers in technology and is a popular choice for those choosing academic, industrial, or entrepreneurial career paths.

3. The B.A. in Engineering Sciences (Electrical) is suitable for careers outside of technology, including managerial, financial, and entrepreneurial career options.

4. The fourth program is a joint B.S. in Electrical Engineering and Computer Science, which offers a unique blend of electrical engineering and computer science courses that retains the rigor of both fields. This degree is a popular choice for those interested in information technology careers.

The program’s educational objectives prepare students for four potential paths. An academic path qualifies graduates to enter a top-tier graduate program conducting research with broad applications or significant consequences, and eventually to teach at an academic or research institution. Graduates following an industrial path can enter a technical path or a managerial path. An entrepreneurial path allows graduates to bring broad knowledge to a startup company, which can deliver a product or service that meets societal needs. Graduates who elect a nontraditional engineering path might complete a professional program in business, law, or medicine, for which their engineering knowledge will be valuable.

PREREQUISITES

All three engineering degree programs require MATH 112 and MATH 115 if applicable, ENAS 151 or MATH 120 or higher, ENAS 130 (CPSC 100 and 112 do not fulfill this requirement), and PHYS 180, 181 or higher (PHYS 170, 171 is acceptable for the B.A. degree). Acceleration credits awarded on entrance can be used to satisfy the MATH 112 and 115 requirements. Students whose preparation exceeds the level of ENAS 151 or MATH 120 are asked to take a higher-level mathematics course instead, such as MATH 222, MATH 225, MATH 226, MATH 255, or MATH 256. Similarly, students whose preparation at entrance exceeds the level of PHYS 180, 181 are asked to take higher-level physics courses instead, such as PHYS 200, 201. Students whose programming skills exceed the level of ENAS 130 are asked to take a more advanced programming course instead, such as CPSC 201; consult with the director of undergraduate studies (DUS).

For students in the Class of 2023 and subsequent classes, prerequisites taken Credit/D/Fail may not be counted toward the requirements of the major.

REQUIREMENTS OF THE MAJOR

Because the introductory courses are common to all three degree programs, students do not usually need to make a final choice before the junior year. Each student’s program must be approved by the DUS.

B.S. degree program in Electrical Engineering The ABET-accredited B.S. in Electrical Engineering requires, beyond the prerequisites, four term courses in mathematics and science and thirteen term courses covering topics in engineering. These courses include:

1. Mathematics and basic science (four term courses): ENAS 194; MATH 222 or MATH 225 or MATH 226; APHY 322 or equivalent; S&DS 238, or S&DS 241, or equivalent.
2. Electrical engineering and related subjects (thirteen term courses): EENG 200, 201, 202, 203, 310, 320, 325, 348, and 481 (the ABET design project senior requirement); and four engineering electives, at least three of which should be at the 400 level. CPSC 365 or CPSC 366, MENG 390, MENG 403, BENG 411, PHYS 430, APHY 458, and all 400-level computer science courses qualify as ABET electives. One of EENG 468 or EENG 469, Advanced Special Projects, also qualify as a 400-level elective.

The introductory engineering courses are designed such that they may be taken concurrently in the sophomore year; for example, in the fall term students may take EENG 200 and EENG 202, followed by EENG 201 and EENG 203 in the spring term. These courses may be taken in any order, with the exception of EENG 203, which requires EENG 200 as a prerequisite. In this case, it would be helpful to take ENAS 194 and/or ENAS 130 in the first year.

A sample ABET-accredited B.S. degree schedule for students who have taken the equivalent of one year of calculus in high school (and thus are not required to take MATH 112 and MATH 115) could include:

First Year: EENG 200, EENG 201, ENAS 151, PHYS 180, and PHYS 181
Sophomore: EENG 202, EENG 203, ENAS 130, ENAS 194, and MATH 222
Junior: EENG 310, EENG 320, EENG 325, EENG 348, S&DS 238, and 1 elective
Senior: APHY 322, EENG 481, and 3 electives

A sample schedule for students who enter into the ABET-accredited B.S. major at the sophomore year could include:

First Year: ENAS 151, ENAS 130, ENAS 194, PHYS 180, and PHYS 181
Sophomore: EENG 200, EENG 201, EENG 202, EENG 203, and MATH 222
Junior: EENG 310, EENG 320, EENG 325, EENG 348, S&DS 238, and 1 elective
Senior: APHY 322, EENG 481, and 3 electives

A sample schedule for students who enter into the ABET-accredited B.S. major in the first year (and are required to take MATH 112 and MATH 115) and only seek to fulfill basic distribution requirements with no engineering courses, could be:

First Year: MATH 112, MATH 115, PHYS 180, PHYS 181, and ENAS 130
Sophomore: ENAS 151, EENG 200, EENG 201, EENG 202, EENG 203, and MATH 222
Junior: ENAS 194, EENG 310, EENG 320, EENG 325, EENG 348, and S&DS 238
Senior: APHY 322, EENG 481, and 4 electives

B.S. degree program in Engineering Sciences (Electrical) This program requires fewer technical courses and allows more freedom for work in technical areas outside the traditional electrical engineering disciplines (e.g., biomedical engineering, mechanical engineering, physics, etc.). It requires thirteen technical term courses beyond the prerequisites, specifically: MATH 222 or MATH 225 or MATH 226; ENAS 194; EENG 200, 201, 202, 203; EENG 471 and/or 472 (the senior requirement), or with permission of the instructor and the DUS, 481; and five or six electives (depending on senior requirement) approved by the DUS, at least three of which must be at the 400 level. All electives listed for the ABET-accredited B.S. major qualify as electives for this degree.

For students who have taken the equivalent of one year of calculus in high school (and thus are not required to take MATH 112 and MATH 115), a sample schedule for the B.S. degree in Engineering Science (Electrical) could be:

First Year: EENG 200, EENG 201, ENAS 151, PHYS 180, and PHYS 181
Sophomore: EENG 202, EENG 203, ENAS 130, ENAS 194, and MATH 222
Junior: 3 electives
Senior: EENG 471 and/or 472, and two or three electives depending on the senior project

The B.S. degree in Engineering Sciences (Electrical) requires fewer specific courses and 4 fewer courses overall than the ABET-accredited degree. Any of the courses required for the ABET-accredited major qualify as electives for this degree, as well as other courses with substantial electrical engineering context, subject to the approval of the DUS. For students entering the major during the sophomore year, or those who need introductory calculus in their first year, sample schedules are similar to those described for the ABET-accredited degree program, with the differences in the B.S. Engineering Sciences (Electrical) degree applied.

The flexibility during the junior and senior years in the schedule above is often used to accommodate a second major, such as Economics, Applied Physics, Computer Science, Physics, or Mechanical Engineering.

B.A. degree program in Engineering Sciences (Electrical) This program is appropriate for those planning a career in fields such as business, law, or medicine where scientific and technical knowledge is likely to be useful. It requires eight technical term courses beyond the prerequisites, specifically: MATH 222, MATH 225, MATH 226 or ENAS 194; EENG 200, 201, 202, and 471 and/or 472 (the senior requirement); and two (or three) approved electives.

Credit/D/Fail For students in the Class of 2023 and subsequent classes, courses taken Credit/D/Fail may not be counted toward the requirements of the major, including the prerequisites.

SENIOR REQUIREMENT
A research or design project carried out in the senior year is required in all three programs and must be approved by the DUS. Students take EENG 471 and/or 472, or 481, present a written report, and make an oral presentation. Students taking both EENG 471 and
It is difficult to enter the major if students do not take mathematics and physical science prerequisites during the first year. Students without high school calculus should take MATH 112 and MATH 115. First-year students with high school calculus typically take MATH 120 or ENAS 151. Potential majors are also encouraged to take PHYS 180 and PHYS 181, or PHYS 200 and PHYS 201, during the first year.
The director of undergraduate studies (DUS) of Electrical Engineering welcomes consultation with students about their program opportunities at any time. For more details, see the department website.

FACULTY OF THE DEPARTMENT OF ELECTRICAL ENGINEERING

Professors  †Hui Cao, †James Duncan, Jung Han, Roman Kuc, Tso-Ping Ma, Rajit Manohar, A. Stephen Morse, Kumpati Narendra, †Daniel Prober, Mark Reed, Peter Schultheiss (Emeritus), †Lawrence Staib, †Hemant Tagare, Hongxing Tang, Leandros Tassulas, J. Rimas Vaisnys, †Y. Richard Yang

Associate Professors  Richard Lethin (Adjunct, Lecturer), Jakub Szefer, †Sekhar Tatikonda, Fengnian Xia

Assistant Professors  Wenjun Hu, Amin Karbasi, Priyadarshini Panda

†A joint appointment with primary affiliation in another department.

View Courses

Courses

EENG 200a, Introduction to Electronics  Jung Han
Introduction to the basic principles of analog and digital electronics. Analysis, design, and synthesis of electronic circuits and systems. Topics include current and voltage laws that govern electronic circuit behavior, node and loop methods for solving circuit problems, DC and AC circuit elements, frequency response, nonlinear circuits, semiconductor devices, and small-signal amplifiers. A lab session approximately every other week. After or concurrently with MATH 115 or equivalent.  QR, WR, SC

EENG 201b, Introduction to Computer Engineering  Priya Panda
Introduction to the theoretical principles underlying the design and programming of simple processors that can perform algorithmic computational tasks. Topics include data representation in digital form, combinational logic design and Boolean algebra, sequential logic design and finite state machines, and basic computer architecture principles. Hands-on laboratory involving the active design, construction, and programming of a simple processor.  QR

EENG 202a, Communications, Computation, and Control  Roman Kuc
Introduction to systems that sense, process, control, and communicate. Topics include information theory and coding (compression, channel coding); network systems (network architecture, routing, wireless networks); signals and systems (linear systems, Fourier techniques, bandlimited sampling); estimation and learning (hypothesis testing, regression, classification); and end-to-end application examples (security, communication systems). MATLAB programming assignments illustrate concepts. Students should have basic familiarity with counting (combinatorics), probability and statistics (independence between events, conditional probability, expectation of random variables, uniform distribution). Prerequisite: MATH 115. AP Stats preferred.  QR

EENG 203b, Circuits and Systems Design  Hong Tang
Introduction to design in a laboratory setting. A wide variety of practical systems are designed and implemented to exemplify the basic principles of systems theory. Systems include audio filters and equalizers, electrical and electromechanical feedback systems, radio transmitters and receivers, and circuits for sampling and reconstructing music. Prerequisites: EENG 200  QR, SC RP

* EENG 235a and EENG 236b, Special Projects  Mark Reed
Faculty-supervised individual or small-group projects with emphasis on laboratory experience, engineering design, or tutorial study. Students are expected to consult the director of undergraduate studies and appropriate faculty members about ideas and suggestions for suitable topics during the term preceding enrollment. These courses may be taken at any time during the student’s career. Enrollment requires permission of both the instructor and the director of undergraduate studies, and submission to the latter of a one- to two-page prospectus signed by the instructor. The prospectus is due in the departmental office one day prior to the date that the student’s course schedule is due. ½ Course cr per term

EENG 310b, Signals and Systems  Staff
Concepts for the analysis of continuous and discrete-time signals including time series. Techniques for modeling continuous and discrete-time linear dynamical systems including linear recursions, difference equations, and shift sequences. Topics include continuous and discrete Fourier analysis, Laplace and Z transforms, convolution, sampling, data smoothing, and filtering. Prerequisite: MATH 115. Recommended preparation: EENG 202.  QR

EENG 320a / PHY 320a, Introduction to Semiconductor Devices  Hong Tang
An introduction to the physics of semiconductors and semiconductor devices. Topics include crystal structure; energy bands in solids; charge carriers with their statistics and dynamics; junctions, p-n diodes, and LEDs; bipolar and field-effect transistors; and device fabrication. Additional lab one afternoon per week. Prepares for EENG 325 and 401. Recommended preparation: EENG 200. PHYS 180 and 181 or permission of instructor  QR, SC

EENG 325a, Electronic Circuits  Fengnian Xia
Models for active devices; single-ended and differential amplifiers; current sources and active loads; operational amplifiers; feedback; design of analog circuits for particular functions and specifications, in actual applications wherever possible, using design-oriented methods. Includes a team-oriented design project for real-world applications, such as a high-power stereo amplifier design. Electronics Workbench is used as a tool in computer-aided design. Additional lab one afternoon per week. Prerequisite: EENG 200.  QR RP
EENG 438b / CPSC 338b, Digital Systems  Rajit Manohar
Development of engineering skills through the design and analysis of digital logic components and circuits. Introduction to gate-level circuit design, beginning with single gates and building up to complex systems. Hands-on experience with circuit design using computer-aided design tools and microcontroller programming. Recommended preparation: EENG 201. QR

EENG 400b, Electronic Materials  Jung Han
Survey and review of fundamental material issues pertinent to modern microelectronic and optoelectronic technology. Topics include band theory, electronic transport, surface kinetics, diffusion, defects in crystals, thin film elasticity, crystal growth, and heteroepitaxy. Formerly EENG 408. Prerequisite: EENG 320 or permission of instructor. QR, SC

EENG 402b / APHY 418b, Advanced Electron Devices  Staff
The science and technology of semiconductor electron devices. Topics include compound semiconductor material properties and growth techniques; heterojunction, quantum well and superlattice devices; quantum transport; graphene and other 2D material systems. Formerly EENG 418. Prerequisite: EENG 320 or equivalent. QR, SC

EENG 406b, Photovoltaic Energy  Fengnian Xia
Survey of photovoltaic energy devices, systems, and applications, including review of optical and electrical properties of semiconductors. Topics include solar radiation, solar cell design, performance analysis, solar cell materials, device processing, photovoltaic systems, and economic analysis. Prerequisite: EENG 320 or permission of instructor. QR, SC

* EENG 422b / CPSC 449b, Computer Architectures and Artificial Intelligence  Richard Lethin
Introduction to the development of computer architectures specialized for cognitive processing, including both offline 'thinking machines' and embedded devices. The history of machines, from early conceptions in defense systems to contemporary initiatives. Instruction sets, memory systems, parallel processing, analog architectures, probabilistic architectures. Application and algorithm characteristics. Formerly EENG 449. Prerequisites: CPSC 100, CPSC 112, or equivalent programming experience; EENG 325, EENG 348, or equivalent circuits and digital logic experience; or permission of instructor. QR

EENG 426b / CPSC 448b / ENAS 876a, Silicon Compilation  Rajit Manohar
An upper-level course on compiling computations into digital circuits using asynchronous design techniques. Emphasis is placed 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. Prerequisite: EENG 201 and introductory programming, or permission of instructor.

EENG 428b, Cloud FPGA  Jakub Szefer
This course is an intermediate to advanced level course focusing on digital design and use of Field Programmable Gate Arrays (FPGAs). In addition, it centers around the new computing paradigm of Cloud FPGAs, where the FPGAs are hosted remotely by cloud providers and accessed remotely by users. The theoretical aspects of the course focus on digital system modeling and design using the Verilog Hardware Description Language (Verilog HDL). 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 also learn about FPGA tools from two major vendors: for Xilinx FPGAs and Intel FPGAs (formerly Altera). The practical aspects focus on designing systems using commercial Cloud FPGA infrastructures: Amazon F1 service (Xilinx FPGAs) or through the Texas Advanced Computing Center (Intel FPGAs). Students learn about cloud computing, interfacing servers to FPGAs, PCIe and AXI protocols, and how to write software that runs on the cloud servers and leverages the FPGAs for acceleration of various computations. Prerequisites: EENG 201 and 348 or permission of the instructor. Students should be familiar with digital design basics and have some experience with Hardware Description Languages such as Verilog or VHDL. QR

* EENG 432a / AMTH 342a, Linear Systems  A Stephen Morse
Introduction to finite-dimensional, continuous, and discrete-time linear dynamical systems. Exploration of the basic properties and mathematical structure of the linear systems used for modeling dynamical processes in robotics, signal and image processing, economics, statistics, environmental and biomedical engineering, and control theory. Prerequisite: MATH 222 or permission of instructor. QR

EENG 434b / MATH 251b / S&DS 351b, Stochastic Processes  Staff
Introduction to the study of random processes including linear prediction and Kalman filtering, Poison counting process and renewal processes, Markov chains, branching processes, birth-death processes, Markov random fields, martingales, and random walks. Applications chosen from communications, networking, image reconstruction, Bayesian statistics, finance, probabilistic analysis of algorithms, and genetics and evolution. Prerequisite: S&DS 241 or equivalent. QR

* EENG 435b / AMTH 362b / CPSC 362b, Decisions and Computations across Networks  A Stephen Morse
For a long time there has been interest in distributed computation and decision making problems of all types. Among these are consensus and flocking problems, the multi-agent rendezvous problem, distributed averaging, gossiping, localization of sensors in a multi-sensor network, distributed algorithms for solving linear equations, distributed management of multi-agent formations, opinion dynamics, and distributed state estimation. 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. Although most of the mathematics need is covered in the lectures, students taking this course should have a working understanding of basic linear algebra. The course is open to all students. Prerequisite: Linear algebra or instructor permission. SC
**EENG 454b / AMTH 364b / S&DS 364b, Information Theory**  Andrew Barron
Foundations of information theory in communications, statistical inference, statistical mechanics, probability, and algorithmic complexity. Quantities of information and their properties: entropy, conditional entropy, divergence, redundancy, mutual information, channel capacity. Basic theorems of data compression, data summarization, and channel coding. Applications in statistics and finance. After STAT 241. **QR**

**EENG 455b, 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. **QR**

**EENG 457a and EENG 457b, Advanced Special Projects**  Mark Reed
Faculty-supervised individual or small-group projects with emphasis on research (laboratory or theory), engineering design, or tutorial study. Students are expected to consult the director of undergraduate studies and appropriate faculty members about ideas and suggestions for suitable topics during the term preceding enrollment. This course may only be taken once and at any appropriate time during the student’s career; it does not fulfill the senior requirement. Enrollment requires permission of both the instructor and the DUS, and submission to the latter of a one- to two-page prospectus approved by the instructor. The prospectus is due to the DUS one day prior to the date that the student’s course schedule is due.

**EENG 471a and EENG 472b, Senior Advanced Special Projects**  Mark Reed
Faculty-supervised individual or small-group projects with emphasis on research (laboratory or theory), engineering design, or tutorial study. Students are expected to consult the director of undergraduate studies and appropriate faculty members about ideas and suggestions for suitable topics during the term preceding enrollment. This course is only open to seniors and is one of the courses that fulfills the senior requirement. Enrollment requires permission of both the instructor and the DUS, and submission to the latter of a one- to two-page prospectus approved by the instructor. The prospectus is due to the DUS one day prior to the date that the student’s course schedule is due.

**EENG 475a / BENG 475a / CPSC 475a, 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. Prerequisite: CPSC 112 and MATH 120, or with permission of instructor. **QR, SC, RP**
* EENG 481b, Advanced ABET Projects  Roman Kuc
Study of the process of designing an electrical device that meets performance specifications, including project initiation and management, part specification, teamwork, design evolution according to real-world constraints, testing, ethics, and communication skills. Design project consists of electronic sensor, computer hardware, and signal analysis components developed by multidisciplinary teams. Prerequisites: EENG 310, 320, 325, and 348.  RP