ELECTRICAL ENGINEERING

Director of undergraduate studies: Mark Reed (mark.reed@yale.edu), 523 BCT, 432-4306; 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.

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 Electrical Engineering and Computer Science B.S. degree, 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.

See Electrical Engineering and Computer Science for the requirements of the joint B.S. degree.

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 250. 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).

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 225; 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. The senior independent research project EENG 471 and/or EENG 472 also qualify (as a single 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 that 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 225; ENAS 194; EENG 200, 201, 202, 203; EENG 471 or 472 (the senior requirement), or with permission of the instructor and the DUS, 481; and six electives 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 EENG 472, and 3 electives

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 that 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, 225, or ENAS 194; EENG 200, 201, 202, and 471 and/or 472 (the senior requirement); and three approved electives.

Credit/D/Fail Courses taken Credit/D/Fail may not be counted toward the requirements of the major.

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, 472, or 481, present a written report, and make an oral presentation. Arrangements to undertake a project in fulfillment of the senior requirement must be made by the end of shopping period in the term in which the student will enroll in the course; by this date, a prospectus approved by the intended faculty adviser must be submitted to the DUS.

ADVISING AND APPROVAL OF PROGRAMS
All Electrical Engineering and Engineering Sciences majors must have their programs approved by the DUS. Arrangements to take EENG 471, 472, or 481 are strongly suggested to be made during the term preceding enrollment in the course. Independent research courses taken before the senior year are graded on a Pass/Fail basis but may be counted toward the requirements of the major.

REQUIREMENTS OF THE MAJOR
ELECTRICAL ENGINEERING, B.S.

Prerequisites MATH 112, 115 if needed; ENAS 151 or MATH 120 or higher; ENAS 130; PHYS 180, 181 or higher
Number of courses 17 term courses beyond prereqs, incl senior req
Specific courses required ENAS 194; MATH 222 or 225; APHY 322; S&DS 238 or S&DS 241; EENG 200, 201, 202, 203, 310, 320, 325, 348
**Distribution of courses** 4 engineering electives, 3 at 400 level  
**Senior requirement** One-term design project (EENG 481)

**ENGINEERING SCIENCES (ELECTRICAL), B.S. AND B.A.**

**Prerequisites** Both degrees – MATH 112, 115; ENAS 151 or MATH 120 or higher; ENAS 130; B.S. – PHYS 180, 181 or higher; B.A. – PHYS 170, 171 or higher

**Number of courses** B.S. – 13 term courses beyond prereqs, incl senior req; B.A. – 8 term courses beyond prereqs, incl senior req

**Specific courses required** B.S. – ENAS 194; MATH 222 or 225; EENG 200, 201, 202, 203; B.A. – 1 from ENAS 194, MATH 222, or 225; EENG 200, 201, 202

**Distribution of courses** B.S. – 6 electives approved by DUS, 3 at 400 level; B.A. – 3 electives approved by DUS

**Senior requirement** B.S. – one-term research or design project (EENG 471 or 472 or, with permission of DUS, 481); B.A. – one-term research or design project (EENG 471 and/or 472)

**FACULTY OF THE DEPARTMENT OF ELECTRICAL ENGINEERING**

**Professors** 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 Tassiulas, J. Rimas Vaišnys, Y. Richard Yang

**Associate Professors** Richard Lethin (Adjunct), Sekhar Tatikonda, Fenngn Xia

**Assistant Professors** Wenjun Hu, Amin Karsabi, Jakub Szefer

**Courses**

**EENG 200a, Introduction to Electronics** Mark Reed  
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, SC

**EENG 201b, Introduction to Computer Engineering** Jakub Szefer  
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** Wenjun Hu
Introduction to systems that sense, process, control, and communicate. Topics include communication systems (compression, channel coding); network systems (network architecture and routing, wireless networks, network security); estimation and learning (classification, regression); and signals and systems (linear systems, Fourier techniques, bandlimited sampling, modulation). MATLAB programming and laboratory experiments illustrate concepts. Prerequisite: MATH 115. QR

**EENG 202b, 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 and 202. QR, SC RP

* EENG 235a and EENG 235b, 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 245b / CPSC 235b, Self-Driving Cars: Theory and Practice** Man-Ki Yoon
This course explores the theory and practice of building self-driving cars using advanced computing technologies. Topics include embedded system programming, sensor fusion, control theory, and introductory planning and navigation techniques using machine learning and computer vision. Students work in small teams to design and build miniaturized self-driving cars that autonomously navigate an indoor track that resembles real road environments. The final project involves driving competitions and project report/presentation of their work. Prerequisite: CPSC 112, 201, 223, or equivalent. Instructor’s permission is required to waive the prerequisites. Enrollment limited to 18. QR

**EENG 310b, Signals and Systems** Kumpati Narendra
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, Introduction to Semiconductor Devices**  Mark Reed  
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

**EENG 348b / CPSC 338b, Digital Systems**  Staff  
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 397a / ENAS 397a, Mathematical Methods in Engineering**  J. Rimas Vaišnys  
Exploration of several areas of mathematics useful in science and engineering; recent approaches to problem solving made possible by developments in computer software. Mathematica and Eureqa are used to investigate and solve problems involving nonlinear differential equations, complex functions, and partial differential equations. Prerequisites: MATH 222, and ENAS 194 or MATH 246, or equivalents; familiarity with computer programming.  QR

**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 408b, CMOS Devices and Beyond**  Jung Han  
The science and technology of modern CMOS devices and circuits, as well as emerging technologies. Topics may include basic CMOS device physics; interface properties of MOS structures; hot-carrier effects; experimental techniques to probe MOS parameters; and scaling of CMOS devices. Prerequisite: EENG 320 or equivalent, or permission by instructor.

* **EENG 422a, 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 426a / 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 428a, 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 434b / MATH 251b / S&D&S 351b, Stochastic Processes**  Amin Karbasi  
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 436a, Systems and Control  
Kumpati Narendra  
Design of feedback control systems with applications to engineering, biological, and economic systems. Topics include state-space representation, stability, controllability, and observability of discrete-time systems; system identification; optimal control of systems with multiple outputs. Prerequisites: ENAS 194, MATH 222 or 225, and EENG 310 or permission of instructor. QR

* EENG 437a / AMTH 437a / ECON 432a / S&DS 430a, Optimization Techniques  
Sekhar Tatikonda  
Fundamental theory and algorithms of optimization, emphasizing convex optimization. The geometry of convex sets, basic convex analysis, the principle of optimality, duality. Numerical algorithms: steepest descent, Newton’s method, interior point methods, dynamic programming, unimodal search. Applications from engineering and the sciences. Prerequisites: MATH 120 and 222, or equivalents. May not be taken after AMTH 237. QR

EENG 445a / BENG 445a, Biomedical Image Processing and Analysis  
James Duncan and Lawrence Staib  
A study of the basic computational principles related to processing and analyzing biomedical images (e.g., magnetic resonance, computed X-ray tomography, fluorescence microscopy). Basic concepts and techniques related to discrete image representation, multidimensional frequency transforms, image enhancement, motion analysis, image segmentation, and image registration. Prerequisite: BENG 352 or EENG 310 or permission of instructors. Recommended preparation: familiarity with probability theory.

EENG 450a, Applied Digital Signal Processing  
J. Rimas Vašnys  
An analysis, by computer, of processing requirements. Relevant probability and estimation theories applied to measurements corrupted by noise. Point estimates and system identification from random processes. MATLAB simulations verify the analysis. Prerequisite: EENG 310 or permission of instructor. QR

* EENG 451b / CPSC 456b, Wireless Technologies and the Internet of Things  
Wenjun Hu  
Fundamental theory of wireless communications and its application explored against the backdrop of everyday wireless technologies such as WiFi and cellular networks. Channel fading, MIMO communication, space-time coding, opportunistic communication, OFDM and CDMA, and the evolution and improvement of technologies over time. Emphasis on the interplay between concepts and their implementation in real systems. Prerequisites: 1) Introductory courses in mathematics, engineering, or computer science covering basics of the following topics: Linux skills, Matlab programming, probability, linear algebra, and Fourier transform; 2) Or by permission of the instructor. The course material will be self-contained as much as possible. The labs and homework assignments require Linux and Matlab skills and simple statistical and matrix analysis (using built-in Matlab functions). There will be a couple of introductory labs to refresh Linux and Matlab skills if needed.

* EENG 452a, Internet Engineering  
Leandros Tassiulas  
Introduction to basic Internet protocols and architectures. Topics include packet-switch and multi-access networks, routing, flow control, congestion control, Internet protocols (IP, TCP, BGP), the client-server model, IP addressing and the domain name system, wireless access networks, and mobile communications. Prerequisite: a college-level course in mathematics, engineering, or computer science, or with permission of instructor. QR

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 468a and EENG 469b, 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