ELECTRICAL ENGINEERING

Director of undergraduate studies: Mark Reed, 523 BCT, 432-4306, mark.reed@yale.edu ; seas.yale.edu/departments/electrical-engineering

FACULTY OF THE DEPARTMENT OF ELECTRICAL ENGINEERING

Professors James Duncan, Jung Han, Roman Kuc, Tso-Ping Ma, A. Stephen Morse, Kumpati Narendra, Mark Reed, Peter Schultheiss (Emeritus), Lawrence Staib, Hemant Tagare, Leandros Tassiotas, J. Rimas Vaišnys, Y. Richard Yang

Associate Professors Minjoo Lee, Richard Lethin (Adjunct), Hongxing Tang, Sekhar Tatikonda

Assistant Professors Wenjun Hu, Amin Karbasi, Jakub Szefer, Fengnian Xia

Electrical Engineering broadly encompasses disciplines such as microelectronics, photonics, computer engineering, signal processing, control systems, and communications, all of which enable and underpin a modern technological society. Three degree programs are offered that allow students to select the level of technical depth appropriate for individual goals. The B.A. in Engineering Sciences (Electrical) is suitable for a career outside technology, in which a student nevertheless benefits from an appreciation of electrical engineering perspectives. The B.S. in Engineering Sciences (Electrical) provides more technical exposure while retaining academic options outside the electrical engineering core area. The B.S. in Electrical Engineering, accredited by the Engineering Accreditation Commission of ABET, Inc., is appropriate for highly motivated students who are interested in learning the scientific fundamentals and the technologies and creative processes of contemporary electrical engineering.

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 managerial or policy-making position that provides significant value to a company. An entrepreneurial path allows graduates to bring broad knowledge to a startup company, which can deliver a device that meets societal needs. Graduates who elect a nontraditional engineering path might complete a professional program such as business, law, or medicine, to which their engineering knowledge can be applied.

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. An interdepartmental program with Computer Science (http://catalog.yale.edu/archive/2015-2016/ycps/subjects-of-instruction/electrical-engineering-computer-science) is also offered, and students can pursue interdisciplinary studies in other areas of engineering and science.

Prerequisites All three degree programs require MATH 112, 115, ENAS 151 or MATH 120 or higher, ENAS 130, 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.

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 in topics in engineering. These courses include:

1. Mathematics and basic science (four term courses): ENAS 194; MATH 222 or 225; APHY 322 or equivalent; STAT 238, 241, or equivalent.
2. Electrical engineering and related subjects (thirteen term courses): EENG 200, 201, 202, 203, 310, 320, 325, 348, 481 (the senior project); and four engineering electives, at least three of which should be at the 400 level. MENG 390, CPSC 365, and all 400-level Computer Science courses qualify as ABET electives.

Each student’s program must be approved by the director of undergraduate studies.

For students who have taken the equivalent of one year of calculus in high school, a typical ABET-accredited B.S. program might include:

<table>
<thead>
<tr>
<th>Freshman</th>
<th>Sophomore</th>
<th>Junior</th>
<th>Senior</th>
</tr>
</thead>
<tbody>
<tr>
<td>EENG 200</td>
<td>EENG 202</td>
<td>APHY 322</td>
<td>EENG 481</td>
</tr>
<tr>
<td>EENG 201</td>
<td>EENG 203</td>
<td>EENG 310</td>
<td>Four electives</td>
</tr>
<tr>
<td>ENAS 151 or MATH 120</td>
<td>ENAS 130</td>
<td>EENG 320</td>
<td></td>
</tr>
<tr>
<td>MATH 222</td>
<td>ENAS 194</td>
<td>EENG 325</td>
<td></td>
</tr>
<tr>
<td>PHYS 180</td>
<td>STAT 241</td>
<td>EENG 348</td>
<td></td>
</tr>
<tr>
<td>PHYS 181</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
For students who start with MATH 112, a typical ABET-accredited B.S. program might include:

**Freshman**
- EENG 201
- ENAS 130
- MATH 112
- MATH 115

**Sophomore**
- EENG 200
- ENAS 151 or MATH 120
- ENAS 194
- MATH 222
- PHYS 180
- PHYS 181

**Junior**
- EENG 202
- EENG 203
- EENG 310
- EENG 320
- EENG 325
- EENG 348

**Senior**
- APHY 322
- EENG 481
- STAT 241
- Four electives

**Four electives**
- MATH 112
- ENAS 194
- Two electives
- MATH 115
- MATH 222
- PHYS 180
- PHYS 181

Faster-paced and slower-paced variations are possible, depending on the student’s level of preparation and commitment to the major; consult with the director of undergraduate studies.

**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., economics or cognitive psychology). 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, or, with permission of the director of undergraduate studies, 481 (the senior project); and six electives approved by the director of undergraduate studies, at least three of which must be at the 400 level.

For students who have taken the equivalent of one year of calculus in high school, a typical program for this degree might include:

**Freshman**
- EENG 200
- ENAS 151 or MATH 120
- MATH 222
- PHYS 180
- PHYS 181

**Sophomore**
- EENG 202
- ENAS 194
- ENAS 130
- EENG 471 or 472
- Three electives

**Junior**
- MATH 201
- ENAS 194
- ENAS 130
- EENG 201
- EENG 203
- Three electives

**Senior**
- EENG 471 or 472
- Three electives

**Senior requirement** A research or design project carried out in the senior year is required in all three programs. The student must take EENG 471, 472, or 481, present a written report, and make an oral presentation. The written report is due in the departmental office by the last day of reading period. Arrangements to undertake a project in fulfillment of the senior requirement must be made by the end of the reading period of the preceding term, when a registration form (available from the departmental office), signed by the intended faculty adviser and the director of undergraduate studies, must be submitted.

**Approval of programs** All Electrical Engineering and Engineering Sciences majors must have their programs approved by the director of undergraduate studies. Arrangements to take EENG 471, 472, or 481 must be made during the term preceding enrollment in the course. Courses taken Credit/D/Fail may not be counted toward the requirements of the major. 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; 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; STAT 238 or 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 or 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 or 472)

Courses

EENG 111b, The Science of Science Fiction  Mark Reed
An exploration of the scientific basis, and inaccuracies, of modern science fiction. Technologies explored include nanotechnology, the theory of relativity, information technology, and environmental sustainability and terraforming.  SC

EENG 200a, Introduction to Electronics  Minjoo Lee
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

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  Sekhar Tatakonda
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 203a or b, Circuits and Systems Design  Fengnian Xia
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 RP

EENG 222b, Nanotechnology  Hongxing Tang
An introduction to the emerging discipline of nanotechnology. The physical effects of nanoscale systems; the synthesis and fabrication of nanostructures; applications ranging from micromachines to electronics to biology. Attention to societal and economic impact, as well as ethical issues created by nanotechnologies. Prerequisites: MATH 115 or equivalent and PHYS 170, 171, or 180, 181, or equivalent; or permission of instructor.  QR, SC

* 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  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. Prerequisites: PHYS 180 and 181 or permission of instructor. Recommended preparation: EENG 200.  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 348b, Digital Systems  Roman Kuc
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 397b / ENAS 397b, Mathematical Methods in Engineering  J. Rimas Vašniys
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 401b / APHY 321b, Semiconductor Silicon Devices and Technology  Tso-Ping Ma
Introduction to integrated circuit technology, theory of semiconductor devices, and principles of device design and fabrication. Laboratory involves the fabrication and analysis of semiconductor devices, including Ohmic contacts, Schottky diodes, p-n junctions, solar cells, MOS capacitors, MOSFETs, and integrated circuits. Prerequisite: EENG 320 or equivalent or permission of instructor.  QR, SC

EENG 404b, Photovoltaic Energy  Minjoo Lee
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 408a, Electronic Materials: Fundamentals and Applications  Jung Han
Survey and review of fundamental issues associated with modern microelectronic and optoelectronic materials. Topics include band theory, electronic transport, surface kinetics, diffusion, materials defects, elasticity in thin films, epitaxy, and Si integrated circuits. Prerequisite: EENG 320 or permission of instructor.  QR, SC

* EENG 410a, Photonics and Optical Electronics  Hongxing Tang
A survey of the enabling components and devices that constitute modern optical communication systems. Focus on the physics and principles of each functional unit, its current technological status, design issues relevant to overall performance, and future directions.  QR, SC

EENG 412b, Energy Semiconductor Fundamentals  Jung Han
The fundamentals of properties and mechanisms in which conventional semiconductor physics intersect with emerging applications. Connections between electrical, mechanical, thermal, and optical properties; contemporary applications in energy, information, and technology. Prerequisite: APHY 448.  SC

EENG 416a, 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 437b / AMTH 437b / ECON 413b, Optimization Techniques  Sekhar Tatlindra
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 442a / 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 444a, Digital Communication Systems  Wenjun Hu
Fundamentals of digital communication system design and information theory. Topics include example coding, modulation techniques in the context of image/video coding and 2D barcodes, and the theoretical background underlying these techniques. Related topics delve into the mathematical foundation of decomposing the systems into separately designed source and channel codes; principles of
converting continuous time wave forms into bits (and vice versa) using algorithms in each component; and usage of vector spaces in signal processing. Prerequisites: knowledge of signals and systems at the level of EENG 310 (mainly Fourier transforms and the sinc function); knowledge of basic probability at the level of STAT 241 (may be taken concurrently). Basic familiarity with Matlab is needed for the initial project. QR

* EENG 449a, Computer Architectures for Cognitive Processing and Machine Learning  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. Prerequisites: EENG 201, 325, and CPSC 112. QR

EENG 450a, Applied Digital Signal Processing  Roman Kuc
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, Wireless Communications  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 / STAT 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 467a / ENAS 467a, Computer Organization and Architecture  Jakub Szefer
Introduction to computer architecture, including computer organization, microprocessors, caches and memory hierarchies, I/O, and storage. Issues surrounding performance, energy, and security; processor benchmarking. Selected readings from current academic literature. Prerequisite: EENG 201, or with permission of instructor. QR

* EENG 471a and EENG 472b, 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. These courses may be taken at any appropriate time during the student's career and may be taken more than once. 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.

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. After MATH 120a or b and CPSC 112a or b, or with permission of instructor. QR, SC RP

* EENG 481b, Advanced ABET Projects  Wenjun Hu
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