ELECTRICAL ENGINEERING

Director of undergraduate studies: J. Rimas Vaišnys, 519 BCT, 432-4253, rimas.vaisnys@yale.edu; seas.yale.edu/departments/electrical-engineering

FACULTY OF THE DEPARTMENT OF ELECTRICAL ENGINEERING

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

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

**Assistant Professors** 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 is also offered (see under Electrical Engineering and Computer Science), 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 or CPSC 112 or higher, 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 or CPSC 112 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>
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<tbody>
<tr>
<td>EENG 200</td>
<td>CPSC 112 or ENAS 130</td>
<td>APHY 322</td>
<td>EENG 481</td>
</tr>
<tr>
<td>EENG 201</td>
<td>EENG 202</td>
<td>EENG 310</td>
<td>Four electives</td>
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<tr>
<td>ENAS 151 or MATH 120</td>
<td>EENG 203</td>
<td>EENG 320</td>
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</tr>
<tr>
<td>MATH 222</td>
<td>ENAS 194</td>
<td>EENG 325</td>
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<tr>
<td>PHYS 180</td>
<td>STAT 241</td>
<td>EENG 348</td>
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For students who start with MATH 112, a typical ABET-accredited B.S. program might include:

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<thead>
<tr>
<th>Freshman</th>
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<th>Junior</th>
<th>Senior</th>
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<tbody>
<tr>
<td>CPSC 112</td>
<td>EENG 200</td>
<td>EENG 202</td>
<td>APHY 322</td>
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<tr>
<td>EENG 201</td>
<td>ENAS 151 or MATH 120</td>
<td>EENG 203</td>
<td>EENG 481</td>
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<tr>
<td>MATH 112</td>
<td>ENAS 194</td>
<td>EENG 310</td>
<td>STAT 241</td>
</tr>
<tr>
<td>MATH 115</td>
<td>MATH 222</td>
<td>EENG 320</td>
<td>Four electives</td>
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<td>PHYS 180</td>
<td>EENG 325</td>
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<td></td>
<td>PHYS 181</td>
<td>EENG 348</td>
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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, 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:

<table>
<thead>
<tr>
<th>Freshman</th>
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<th>Junior</th>
<th>Senior</th>
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<tbody>
<tr>
<td>EENG 200</td>
<td>CPSC 112</td>
<td>Three electives</td>
<td>EENG 471</td>
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<tr>
<td>EENG 201</td>
<td>EENG 202</td>
<td>Three electives</td>
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<tr>
<td>ENAS 151 or MATH 120</td>
<td>EENG 203</td>
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<tr>
<td>MATH 222</td>
<td>ENAS 194</td>
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<td>PHYS 180</td>
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<td>PHYS 181</td>
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<tbody>
<tr>
<td>CPSC 112</td>
<td>EENG 200</td>
<td>EENG 202</td>
<td>EENG 471</td>
</tr>
<tr>
<td>EENG 201</td>
<td>ENAS 151 or MATH 120</td>
<td>EENG 203</td>
<td>Four electives</td>
</tr>
<tr>
<td>MATH 112</td>
<td>ENAS 194</td>
<td>Two electives</td>
<td></td>
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<tr>
<td>MATH 115</td>
<td>MATH 222</td>
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<td>PHYS 180</td>
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<td>PHYS 181</td>
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</tbody>
</table>

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. The implied flexibility during the junior and senior years in the schedules above is often used to accommodate a second major, such as Economics, or to master a related technical area, such as recent developments in biology or environmental studies.

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

**Senior requirement** A research or design project carried out in the fall term of the senior year is required in all three programs. The student must take EENG 471 or 472, 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.

**REQUIREMENTS OF THE MAJOR**

**ELECTRICAL ENGINEERING, B.S.**

**Prerequisites** MATH 112, 115; ENAS 151 or MATH 120 or higher; ENAS 130 or CPSC 112 or higher; 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
Courses

EENG 200a, Introduction to Electronics  Tso-Ping Ma
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  Robert Sadowski and 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 Tatikonda
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  Hongxing Tang and 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 235a and EENG 236b, Special Projects  J. Rimas Vašnys
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  Hongxing Tang
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

Prerequisites  Both degrees — MATH 112, 115; ENAS 151 or MATH 120 or higher; ENAS 130 or CPSC 112 or higher; 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, with permission of DUS, 481); B.A. — one-term research or design project (EENG 471)
EENG 348a, 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 Vaiknys
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 401bG / APHY 321bG, 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 406, Photovoltaic Energy
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 410bG, Photonics and Optical Electronics  Jung Han
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 418bG / APHY 418b, Heterojunction Devices  Mark Reed
The science and technology of semiconductor and semiconductor device physics, with emphasis on contemporary heterojunction devices. Compound semiconductor material properties and growth techniques; high speed and millimeter-wave devices; quantum well and superlattice devices; and device modeling. A laboratory component involves device fabrication and measurement. Prerequisite: APHY 439 or equivalent. QR, SC

EENG 425a, Introduction to VLSI System Design  Richard Lethin
Chip design; integrated devices, circuits, and digital subsystems needed for design and implementation of silicon logic chips. CMOS fabrication overview, complementary logic circuits, design methodology, computer-aided design techniques, timing, and area estimation. Exploration of recent and future chip technologies. A course project is the design, through layout, of a digital CMOS subsystem chip; selected projects are fabricated for students. Prerequisite: familiarity with computer programming and with circuits at the level of introductory physics. QR

EENG 436aG, 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 437aG / AMTH 437bG, Optimization Techniques  A. Stephen Morse and 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. QR

EENG 438aG, Neural Networks for Pattern Recognition, Identification, and Control  Kumpati Narendra
Design of artificial neural networks (ANN) for approximation, pattern recognition, identification, and control. Introduction to the theory of artificial neural networks and linear adaptive control; adaptive identification and control problems in nonlinear dynamical systems. Applications in engineering and biology. Prerequisite: EENG 436 or permission of instructor. QR

EENG 441aG / 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 445aG / BENG 445aG, Biomedical Image Processing and Analysis  James Duncan and Lawrence Staib
A study of the basic computational principles related to processing and analysis of 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 454b / AMTH 364b / STAT 364b, Information Theory** Andrew Barron


*EENG 471a and EENG 472b, Advanced Special Projects* J. Rimas Vaišnys

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 481b, Advanced ABET Projects* Robert Sadowski and staff

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.