

# ELECTRICAL ENGINEERING

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Electrical Engineering broadly encompasses disciplines such as microelectronics, photonics, computer engineering, signal processing, control systems, and communications. Three degree programs are offered that allow students to select the level of technical depth appropriate for individual goals. 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 B.S. in Engineering Sciences (Electrical) provides similar technical exposure while retaining academic options outside the electrical engineering core area. 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 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.

## 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.

## 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. An interdepartmental program with Computer Science is also offered, and students can pursue interdisciplinary studies in other areas of engineering and science. 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 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; S&DS 238, S&DS 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.

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

First-Year	Sophomore	Junior	Senior
EENG 200	EENG 202	APHY 322	EENG 481
EENG 201	EENG 203	EENG 310	Four electives
ENAS 151 or MATH 120	ENAS 130	EENG 320	
MATH 222	ENAS 194	EENG 325	
PHYS 180	S&DS 241	EENG 348	
PHYS 181			

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.

**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 DUS, 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:

First-Year	Sophomore	Junior	Senior
EENG 200	EENG 202	Three electives	EENG 471 or 472
EENG 201	EENG 203		Three electives
ENAS 151 or MATH 120	ENAS 130		
MATH 222	ENAS 194		
PHYS 180			
PHYS 181			

As with the ABET degree, the introductory engineering courses 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.

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

**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 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. The student must 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 and the DUS must be submitted.

#### 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; 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 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)

#### 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 Tassioulas, J. Rimas Vaišnys, Y. Richard Yang

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

**Assistant Professors** Wenjun Hu, Amin Karbasi, 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 203b, Circuits and Systems Design** Hongxing 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 236a or b, 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. Additional sections offered in Beijing, China. See under Peking University–Yale University Joint Undergraduate Program. ½ Course cr

### **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** 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

### **EENG 348b / 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 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 Eureka 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 410a, 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 416a, CMOS Devices and Beyond** Tso-Ping Ma

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 425a, Introduction to VLSI System Design** Rajit Manohar

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 437a / AMTH 437a / ECON 413a / 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 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 445a / BENG 445a, 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 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 / CPSC 456b / CPSC 556b, 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 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 or b, 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.

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