

ELECTRICAL ENGINEERING

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The Electrical Engineering (EE) program at Yale College is designed to equip students with the skills and knowledge needed to thrive in today's rapidly evolving technological landscape. Our undergraduate program broadly encompasses disciplines such as microelectronics, photonics, energy, semiconductor technology, computer engineering, signal and information processing, decision and control systems, and communications. Students engage in hands-on projects and experimental design, honing their ability to analyze complex problems and communicate their findings effectively. Whether pursuing careers in government, industry, or academia, graduates of our program are prepared to make significant contributions to society and address pressing global challenges.

Three electrical engineering degree programs are offered, as well as a joint degree between the electrical engineering and computer science departments.

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

Upon graduation, Yale's B.S. Electrical Engineering (ABET) students are expected to achieve "student outcomes" as defined by ABET and the program. The Electrical Engineering major produces graduates who demonstrate: (1) an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics; (2) an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors; (3) an ability to communicate effectively with a range of audiences; (4) an ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts; (5) an ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives; (6) an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions; (7) an ability to acquire and apply new knowledge as needed, using appropriate learning strategies.

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

3. The **B.A. in Engineering Sciences (Electrical)** is suitable for careers outside of technology, including managerial, financial, and entrepreneurial career options.
4. The fourth program is a joint **B.S. in Electrical Engineering and Computer Science**, which offers a unique blend of electrical engineering and computer science courses that retains the rigor of both fields. This degree is a popular choice for those interested in information technology careers.

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

PREREQUISITES

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

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

REQUIREMENTS OF THE MAJOR

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

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

1. Mathematics and basic science (four term courses): ENAS 194; MATH 222 or MATH 225 or MATH 226; APHY 322 or equivalent; S&DS 238, or S&DS 241, or equivalent.
2. Electrical engineering and related subjects (thirteen term courses): EENG 200, 201, 202, 203, 310, 320, 325, 348, and 481 (the ABET design project senior requirement); and four engineering electives, at least three of which should be at the 400 level. CPSC 365 or CPSC 366, MENG 390L, MENG 400, MENG 403, BENG 411,

PHYS 430, APHY 458, and all 400-level computer science courses qualify as ABET electives. One of EENG 468 or EENG 469, Advanced Special Projects, also qualify as a 400-level elective.

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

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

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

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

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

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

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

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

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

First Year: EENG 200, EENG 201, ENAS 151, PHYS 180, and PHYS 181

Sophomore: EENG 202, EENG 203, ENAS 130, ENAS 194, and MATH 222

Junior: 3 electives

Senior: EENG 471 and/or 472, and two or three electives depending on the senior project

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

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

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

Credit/D/Fail Courses, including the prerequisites, 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 and/or 472, or EENG 481, present a written report, and make an oral presentation. EENG 481 is required for students earning the B.S. degree in Electrical Engineering (ABET). Students taking both EENG 471 and 472, Senior Advanced Special Projects, may count one as an elective. Arrangements to undertake a project in fulfillment of the senior requirement must be made by the end of the course selection 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 (EENG 468 or EENG 469) are graded on a Pass/Fail basis, and one (1) can be counted toward the requirements of the major.

SUMMARY OF MAJOR REQUIREMENTS

ELECTRICAL ENGINEERING, B.S.

Prerequisites MATH 112, 115 if needed; ENAS 151 or MATH 120 or higher; ENAS 130 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 MATH 225 or MATH 226; 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) with DUS approval

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

Prerequisites *Both degrees* – MATH 112, 115; ENAS 151 or MATH 120 or higher; ENAS 130 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 MATH 225 or MATH 226; EENG 200, 201, 202, 203; *B.A.* – 1 from ENAS 194, MATH 222, MATH 225, or MATH 226; EENG 200, 201, 202

Distribution of courses *B.S.* – 5 or 6 electives, depending on senior req, approved by DUS, 3 at 400 level; *B.A.* – 2 or 3 electives, depending on senior req, approved by DUS

Senior requirement *B.S.* – one or two-term research or design project, EENG 471 and/or 472, or EENG 481, approved by DUS; *B.A.* – one or two-term research or design project, EENG 471 and/or 472, approved by DUS

Electrical Engineering (ABET), B.S. Degree

Prerequisites

- MATH 112 if needed
- MATH 115 if needed
- ENAS 151 or MATH 120 or higher
- ENAS 130 or higher
- PHYS 180 and PHYS 181 or higher

Requirements

17 courses (17 credits) beyond the prerequisites, but including the senior requirement

- ENAS 194
- MATH 222 or MATH 225 or MATH 226
- APHY 322
- S&DS 238 or S&DS 241
- EENG 200
- EENG 201
- EENG 202
- EENG 203
- EENG 310
- EENG 320
- EENG 325

- EENG 348
- 4 engineering electives, 3 at 400 level
- EENG 481

Engineering Sciences (Electrical), B.S. Degree

Prerequisites

- MATH 112 if needed
- MATH 115 if needed
- ENAS 151 or MATH 120 or higher
- ENAS 130 or higher
- PHYS 180, PHYS 181 or higher

Requirements

13 courses (13 credits) beyond the prerequisites, but including the senior requirement

- ENAS 194
- MATH 222 or MATH 225 or MATH 226
- EENG 200
- EENG 201
- EENG 202
- EENG 203
- 5-6 electives (depending on the senior requirement), 3 of which must be at 400 level
- one or two-term research or design project, EENG 471 and/or EENG 472, or EENG 481 with DUS approval

Engineering Sciences (Electrical), B.A. Degree

Prerequisites

- MATH 112
- MATH 115
- ENAS 151 or MATH 120 or higher
- ENAS 130 or higher
- PHYS 170, PHYS 171 or higher

Requirements

8 courses (8 credits), beyond the prerequisites, but including the senior requirement

- ENAS 194, MATH 222, MATH 225, or MATH 226
- EENG 200
- EENG 201
- EENG 202
- 2 or 3 electives, depending on the senior requirement
- one or two-term research or design project, EENG 471 and/or EENG 472, with DUS approval

Electrical engineering (EE) deals with the study and application of electricity, electronics, and electromagnetism, including such topics as digital computers, power engineering, telecommunications, control systems, radio-frequency engineering, signal processing, instrumentation, and microelectronics. Electrical engineers were responsible for inventing much of today's sophisticated technology, such as the Internet, land and air transportation systems, medical devices, and many other modern features of everyday life. Yale electrical engineer graduates are highly respected and sought after for work not only in the engineering profession, but in business, start-up ventures, management consulting, investment banking, venture finance, medicine, and intellectual property law.

Four degree programs allow students to select the level of technical depth appropriate for their individual goals.

1. The B.S. in Electrical Engineering is accredited by the Engineering Accreditation Commission of ABET, Inc., and is the department's most intensive major program. Students are trained for engineering practice, and the curriculum culminates in a major team design project that incorporates engineering standards and realistic constraints. This program is appropriate for highly motivated students who have a strong interest in the engineering profession.
2. The B.S. in Engineering Sciences (Electrical) requires a somewhat smaller number of courses than the ABET-accredited B.S. degree, in exchange for more flexibility in course selection. This program is appropriate for students who have interest in continuing either in the engineering profession or in other postgraduate options such as graduate or professional school.
3. The B.A. in Engineering Sciences (Electrical) requires substantially fewer engineering courses. It is suitable for careers outside technology in which a student nevertheless benefits from an appreciation of electrical engineering perspectives, and it is appropriate as a second major.
4. The fourth major is a joint Electrical Engineering and Computer Science B.S. degree, and has a unique blend of electrical engineering and computer science that retains the rigor of both fields. This degree is a popular choice for those interested in information technology careers.

First-year students interested in the Electrical Engineering major typically take EENG 200 and EENG 201, both excellent introductions to the major. In the sophomore year students take EENG 202 and EENG 203. However, EENG 200 and EENG 201 need not be taken in the first year since these courses are designed such that EENG 200 and EENG 202 can be taken concurrently; as can EENG 201 and EENG 203.

It is difficult to enter the major if students do not take mathematics and physical science prerequisites during the first year. Students without high school calculus should take MATH 112 and MATH 115. First-year students with high school calculus typically take MATH 120 or ENAS 151. Potential majors are also encouraged to take PHYS 180 and PHYS 181, or PHYS 200 and PHYS 201, during the first year.

The director of undergraduate studies (DUS) of Electrical Engineering welcomes consultation with students about their program opportunities at any time. For more details, see the department website.

FACULTY OF THE DEPARTMENT OF ELECTRICAL ENGINEERING

Professors †Hui Cao, †James Duncan, Jung Han, Roman Kuc, Rajit Manohar, A. Stephen Morse, Kumpati Narendra, †Daniel Prober, Peter Schultheiss (*Emeritus*), †Lawrence Staib, †Hemant Tagare, Hongxing Tang, Leandros Tassioulas, J. Rimantas Vaišnys, †Y. Richard Yang

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

Assistant Professors Wenjun Hu, Amin Karbasi, Priyadarshini Panda

†A joint appointment with primary affiliation in another department.

View Courses

Courses

EENG 200a, Introduction to Electronics Staff

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

EENG 201b, Introduction to Computer Engineering Priya Panda

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

EENG 202a, Introduction to Communications and Control Anna Gilbert

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

EENG 203b, Circuits and Systems Design Hong Tang

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

*** EENG 235a, Special Projects** Rajit Manohar and Fengnian Xia

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

EENG 310b, Signals and Systems Dionysis Kalogierias

Signal and system theory, having its roots at a great extent on classical and modern harmonic analysis, has played an instrumental role in the development of several transformative technologies during the 20th and 21st centuries. Two such examples are communication systems (analog, digital, wired, wireless), and compressive sensing and sparse approximations. This core course provides a comprehensive first exposition to signal and system theory, and mainly covers the following content: definitions/classifications/modeling of signals and systems in continuous and discrete-time; linear system theory (impulse response, frequency response, linear difference/differential equations); convolutions (continuous and discrete); Fourier series; Fourier transform (continuous and discrete-time); Laplace transform and Z-transform. Prior knowledge of advanced calculus of one variable and some elementary real analysis will be very useful (something like MATH 115), although it is not required strictly. QR

EENG 320a / APHY 320a, Semiconductor Devices Hong Tang

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

EENG 325a, Microelectronic 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 400a, Electronic Materials Mengxia Liu

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

EENG 402b / APHY 418b, Advanced Electron Devices Mengxia Liu

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

EENG 406b, Photovoltaic Energy Fengnian Xia

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

EENG 420b / CPSC 420b, Computer Architecture Abhishek Bhattacharjee

This course offers a treatment of computer architectures for high-performance and power/energy-efficient computer systems. Topics include the foundations of general-purpose computing, including instruction set architectures, pipelines, superscalar and out-of-order execution, speculation, support for precise exceptions, and simultaneous multi-threading. We also cover domain-specific hardware (e.g., graphics processing units), and ongoing industry efforts to elevate them to the status of first-class computing units. In tandem, we cover topics relevant to both general-purpose and domain-specific computing, including memory hierarchies, address translation and virtual memory, on-chip networks, machine learning techniques for resource management, and coherence techniques. If time permits, we will study the basics of emerging non-classical computing paradigms like neuromorphic computing. Overall, this course offers insights on how the computing industry is combating the waning of traditional technology scaling via acceleration and heterogeneity. Prerequisites: CPSC 323, 223, and 202. This is a programming-intensive course, so comfort with large programming projects is essential.

*** EENG 424b, Computer Hardware Security** Jakub Szefer

Computer hardware security is one of the most important and challenging areas in computer engineering. Securing computers is essential to safeguarding personal information, intellectual property, and the national infrastructure at large. While technology is constantly changing, the fundamental problems of securing computers remain the same. With each new technology, similar problems of information leakage and different types of covert- and side- channel attacks emerge. This course provides an in-depth examination of computers and their hardware-based security issues. The operation of the hardware, from transistors to processor microarchitectures, has intimate impact on the security of the whole system. Often, software or algorithms executing on a computer have no control over, or detailed access to, the underlying hardware. Yet, the operation of the hardware and different types of side-effects, such as changing timing, changing power consumption, EM emanations, or different types of crosstalk effects lead to information leakage. To understand the hardware-

based security issues, and how to prevent them, the course focuses on classical microprocessors, accelerators such as Field Programmable Gate Arrays, as well as emerging technologies such as Quantum Computers. For the different types of computers, the course teaches students about the various hardware security issues, and students are able to experiment and perform hands-on exercises to demonstrate different types of information leaks. Students also learn about latest research through reading and presenting research papers in-class. Prerequisite: EENG 348 or CPSC 323 or with instructor's approval. QR

EENG 426a / CPSC 448a / 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 Computing with FPGAs Jakub Szefer
This course is an intermediate to advanced level course focusing on digital design and use of Field Programmable Gate Arrays (FPGAs). The course centers around the new cloud computing paradigm of using FPGAs that 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 learn about topics ranging from high-level ideas about cloud computing to low-level details of interfacing servers to FPGAs, PCIe protocol, AXI protocol, and other common communication protocols between hardware modules or between the FPGAs and the host computer, including Serial, SPI, and I2C. Students also learn about and use FPGA tools from Xilinx, but course also touches on tools available from Intel (formerly Altera) as well as open-source tools. The practical aspects of the course include semester-long projects leveraging commercial or in-lab remote FPGAs, based on the project selected by students. 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 431a, Foundations of Data Science Amin Karbasi
Recent advances in data science have enabled us to make tremendous progress in various fields including robotics, machine learning, computer vision, medicine, etc. This course provides an easy, yet rigorous, introduction to the mathematical and algorithmic foundations of data science. We cover key ideas that have led to such progress from statistics to optimization. The course is organized around three themes: What is learning? What algorithms can we use to learn? How can we optimize resources for efficient learning? Prerequisites: MATH 120, MATH 222, CPSC 365, and STAT 241. SC

* **EENG 432a / AMTH 342a, Linear Systems** A Stephen Morse
Introduction to finite-dimensional, continuous, and discrete-time linear dynamical systems. Exploration of the basic properties and mathematical structure of the

linear systems used for modeling dynamical processes in robotics, signal and image processing, economics, statistics, environmental and biomedical engineering, and control theory. Prerequisite: MATH 222 or permission of instructor. QR

EENG 434b / MATH 251b / S&DS 351b, Stochastic Processes Ilias Zadik

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

*** EENG 435b / AMTH 362b / CPSC 362b, Decisions and Computations across**

Networks A Stephen Morse

For a long time there has been interest in distributed computation and decision making problems of all types. Among these are consensus and flocking problems, the multi-agent rendezvous problem, distributed averaging, gossiping, localization of sensors in a multi-sensor network, distributed algorithms for solving linear equations, distributed management of multi-agent formations, opinion dynamics, and distributed state estimation. The aim of this course is to explain what these problems are and to discuss their solutions. Related concepts from spectral graph theory, rigid graph theory, non-homogeneous Markov chain theory, stability theory, and linear system theory are covered. Although most of the mathematics need is covered in the lectures, students taking this course should have a working understanding of basic linear algebra. The course is open to all students. Prerequisite: Linear algebra or instructor permission.

SC

EENG 439a, Neural Networks and Learning Systems Priya Panda

Neural networks (NNs) have become all-pervasive giving us self-driving cars, Siri Voice assistants, Alexa, and much more. While deep NNs deliver state-of-the-art accuracy on many artificial intelligence tasks, it comes at the cost of high computational complexity. Accordingly, designing efficient hardware architectures for deep neural networks is an important step towards enabling the wide deployment of NNs, particularly in low-power computing platforms, such as, mobiles, embedded Internet of Things (IoT) and drones. This course aims to provide a thorough overview on deep learning techniques, while highlighting the key trends and advances toward efficient processing of deep learning in hardware systems, considering algorithm-hardware co-design techniques. Prerequisites: MATH 222 or CPSC 202, EENG 201, and knowledge of Python programming.

EENG 445a / BENG 445a, Biomedical Image Processing and Analysis Lawrence Staib and James Duncan

This course is an introduction to biomedical image processing and analysis, covering image processing basics and techniques for image enhancement, feature extraction, compression, segmentation, registration and motion analysis including traditional and machine learning techniques. Student learn the fundamentals behind image processing and analysis methods and algorithms with an emphasis on biomedical applications.

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 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 Staff

Foundations of information theory in communications, statistical inference, statistical mechanics, probability, and algorithmic complexity. Quantities of information and their properties: entropy, conditional entropy, divergence, redundancy, mutual information, channel capacity. Basic theorems of data compression, data summarization, and channel coding. Applications in statistics and finance. After STAT 241. QR

*** EENG 455b, Network Algorithms and Stochastic Optimization** Leandros Tassiulas

This course focuses on resource allocation models as well as associated algorithms and design and optimization methodologies that capture the intricacies of complex networking systems in communications computing as well as transportation, manufacturing, and energy systems. Max-weight scheduling, back-pressure routing, wireless opportunistic scheduling, time-varying topology network control, and energy-efficient management are sample topics to be considered, in addition to Lyapunov stability and optimization, stochastic ordering, and notions of fairness in network resource consumption. QR

*** EENG 468a, Advanced Special Projects** Rajit Manohar and Fengnian Xia

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, Senior Advanced Special Projects** Rajit Manohar and Fengnian Xia

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