ELECTRICAL ENGINEERING

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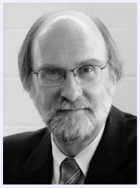
www.ee.columbia.edu



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Contemporary electrical engineering is a broad discipline that encompasses a wide range of activities. A common theme is the use of electrical and electromagnetic signals for the generation, transmission, processing, storage, conversion, and control of information and energy. An equally important aspect is the human interface and the role of individuals as the sources and recipients of information. The rates at which information is transmitted today range from megabits per second to gigabits per second and in some cases, as high as terabits per second. The range of frequencies over which these processes are studied extends from direct current (i.e., zero frequency), to microwave and optical frequencies.

The need for increasingly faster and more sophisticated methods of handling information poses a major challenge to the electrical engineer. New materials, devices, systems, and network concepts are needed to build the advanced communications and information handling systems of the future. Previous innovations in electrical engineering have had a dramatic impact on the way in which we work and live: the transistor, integrated circuits, computers, radio and television, satellite transmission systems, lasers, fiber optic transmission systems, and medical electronics.

The faculty of the Electrical Engineering Department at Columbia University is dedicated to the continued development of further innovations through its program of academic instruction and research. Our undergraduate academic program in electrical engineering is designed to prepare the student for a career in industry or business by providing her or him with a thorough foundation of the fundamental concepts and analytical tools of contemporary electrical engineering. A wide range of elective courses permits the student to emphasize specific disciplines such as telecommunications, microelectronics, digital systems, or photonics. Undergraduates have an opportunity to learn firsthand about current research activities by participating in a program of undergraduate research projects with the faculty.

A master's level program in electrical engineering permits the graduate student to further specialize her/his knowledge and skills within a wide range of disciplines. For those who are interested in pursuing a career in teaching or research, our Ph.D. program offers the opportunity to conduct research under faculty super-vision at the leading edge of technology and applied science. Research seminars are offered in a wide range of areas, including telecommunications, very large scale integrated circuits, photonics, and microelectronics.

The Electrical Engineering Department, along with the Computer Science Department, also offers B.S. and M.S. programs in computer engineering. Details on those programs can be found in the Computer Engineering section in this bulletin.

Research Activities

The research interests of the faculty encompass a number of rapidly growing areas, vital to the development of future technology, that will affect almost every aspect of society: communications and information processing; solid-state devices; ultrafast optics and photonics; microelectronic circuits, integrated systems and computer-aided design; systems biology; and electromagnetics and plasmas. Details on all of these areas can be found at www .ee.columbia.edu/research.

Communications research focuses on wireless communication, multimedia networking, real-time Internet, lightwave (fiber optic) communication networks, optical signal processing and switching, service architectures, network management and control, the processing of image and video information, and media engineering. Current studies include wireless and mobile computing environments, broadband kernels, object-oriented network management, real-time monitoring and control, lightwave network architectures, lightweight protocol design, resource allocation and networking games, real-time Internet services, future all-digital HDTV systems, coding and modulation.

Solid-state device research is conducted in the Columbia Microelectronics Sciences Laboratories. This is an interdisciplinary facility, involving aspects of electrical engineering and applied physics. It includes the study of semiconductor physics and devices, optical electronics, and quantum optics. The emphasis is on laser processing and diagnostics for submicron electronics, fabrication of compound semiconductor optoelectronic devices by molecular beam epitaxy, physics of superlattices and quantum wells, and interface devices such as Schottky barriers, MOS transistors, heterojunctions, and bipolar transistors. Another area of activity is the physics and chemistry of microelectronics packaging.

Research in photonics includes development of semi conductor light sources such as LEDs and injection lasers, fabrication and analysis of quantum confined structures, photo conductors, pin diodes, avalanche photodiodes, optical interconnects, and quantum optics. A major effort is the picosecond optoelectronics program, focusing on the development of new devices and their applications to high-speed optoelectronic measurement systems, photonic switching, and optical logic. In addition, research is being performed in detection techniques for optical communications and radar. Members of the photonics group play a leading role in a multi-university consortium: The National Center for Integrated Photonics Technology.

Integrated systems research involves the analysis and design of analog, digital, and mixed-signal microelectronic circuits and systems. These include novel signal processors and related systems, data converters, radio frequency circuits, low noise and low power circuits, and fully integrated analog filters that share the same chip with digital logic. VLSI architectures for parallel computation, packet switching, and signal processing are also under investigation. Computer-aided design research involves the development of techniques for the analysis and design of large-scale integrated circuits and systems.

Electromagnetics research ranges from the classical domains of microwave generation and transmission and wave propagation in various media to modern applications involving lasers, optical fibers, plasmas, and solid-state devices. Problems relevant to controlled thermo-nuclear fusion are under investigation.

Laboratory Facilities

Current research activities are fully supported by more than a dozen well-equipped research laboratories run by the department. Specifically, laboratory research is conducted in the following laboratories: Multimedia Networking Laboratory, Lightwave Communications Laboratory, Systems Laboratory, Image and Advanced Television Laboratory, Laser Processing Laboratory, Molecular Beam Epitaxy Laboratory, Surface Analysis Laboratory, Microelectronics Fabrication Laboratory, Device Measurement Laboratory, Ultrafast Optoelectronics Laboratory, Columbia Integrated Systems Laboratory (CISL), Lightwave Communications Laboratory, Photonics Laboratory, Plasma Physics Laboratory (in conjunction with the Department of Applied Physics).

Laboratory instruction is provided in the Introduction to Electrical Engineering Laboratory, Marcellus-Hartley Electronics Laboratory, Microprocessor Laboratory, Microwave Laboratory, Optical Electronics Laboratory, Solid-State Laboratory, VLSI Design Laboratory, and Student Projects Laboratory, all on the twelfth floor of the S. W. Mudd Building.

UNDERGRADUATE PROGRAM

The educational objective of the Electrical Engineering program, in support of the mission of the School, is to prepare graduates to achieve success in one or more of the following within a few years after graduation:

A. Graduate or professional studies—as evidenced by admission to a top-tier program, attainment of advanced degrees, research contributions, or professional recognition.
B. Engineering practice—as evidenced by entrepreneurship; employment in industry, government, academia, or nonprofit organizations in engineering; patents; or professional recognition.
C. Careers outside of engineering that take advantage of an engineering education—as evidenced by contributions appropriate to the chosen field.

The B.S. program in electrical engineering at Columbia University seeks to provide a broad and solid foundation in the current theory and practice of electrical engineering, including familiarity with basic tools of math and science, an ability to communicate ideas, and a humanities background sufficient to understand the social implications of engineering practice. Graduates should be qualified to enter the profession of engineering, to continue toward a career in engineering research, or to enter other fields in which engineering knowledge is essential. Required nontechnical courses cover civilization and culture, philosophy, economics, and a number of additional electives. English communication skills are an important aspect of these courses. Required science courses cover basic chemistry and physics, whereas math requirements cover calculus, differential equations, probability, and linear algebra. Basic computer knowledge is also included, with an introductory course on using engineering workstations and two rigorous introductory computer science courses. Core electrical engineering

ELECTRICAL ENGINEERING PROGRAM: FIRST AND SECOND YEARS EARLY-STARTING STUDENTS

	SEMESTER I	SEMESTER II	SEMESTER III	SEMESTER IV
MATHEMATICS	MATH V1101 (3)	MATH V1102 (3)	MATH V1201 (3)	MATH V1202 (3) **and** APMA E2101 (3)[1]
PHYSICS (three tracks, choose one)	C1401 (3) → C1601 (3.5) → C2801 (4.5) →	C1402 (3) C1602 (3.5) C2802 (4.5)		
CHEMISTRY	one-semester lecture (3–4) C1403 **or** C1404 **or** C3045 **or** C1604			
CORE REQUIRED COURSES	ELEN E1201 (3.5) Introduction to electrical engineering (either semester)		ELEN E3201 (3.5) Circuit analysis ELEN E3801 (3.5) Signals and systems	ELEN E3331 (3) Electronic circuits CSEE E3827 (3) Fund. of computer sys.
REQUIRED LABS			ELEN E3081 (1)[2] Circuit analysis lab ELEN E3084 (1)[2] Signals and systems lab	ELEN E3083 (1)[2] Electronic circuits lab ELEN E3082 (1)[2] Digital systems lab
ENGLISH COMPOSITION (three tracks, choose one)	C1010 (3) Z1003 (0) → Z0006 (0) →	C1010 (3) Z1003 (0) →	C1010 (3)	
REQUIRED NONTECHNICAL ELECTIVES	HUMA C1001, COCI C1101, **or** Major Cultures (3–4); HUMA W1121 **or** W1123 (3); HUMA C1002, COCI C1102, **or** Global Core (3–4); ECON W1105 (4) **and** W1155 recitation (0); some of these courses can be postponed to the junior or senior year, to make room for taking the above electrical engineering courses.			
COMPUTER SCIENCE	ENGI E1006 (3) either semester[3]			
PHYSICAL EDUCATION	C1001 (1)	C1002 (1)		
THE ART OF ENGINEERING	ENGI E1102 (4) either semester			

[1] APMA E2101 may be replaced by MATH E1210 and either APMA E3101 or MATH V2010.

[2] If possible, these labs should be taken along with their corresponding lecture courses.

[3] ENGI E1006 may not be offered every semester. See www.ee.columbia.edu for more discussion about the Computer Science sequences.

courses cover the main components of modern electrical engineering and illustrate basic engineering principles. Topics include a sequence of two courses on circuit theory and electronic circuits, one course on semiconductor devices, one on electromagnetics, one on signals and systems, one on digital systems, and one on communications or networking. Engineering practice is developed further through a sequence of laboratory courses, starting with a first-year course to introduce hands-on experience early and to motivate theoretical work. Simple creative design experiences start immediately in this first-year course. Following this is a sequence of lab courses that parallel the core lecture courses. Opportunities for exploring design can be found both within these lab courses and in the parallel lecture courses, often coupled with experimentation and computer simulation, respectively. The culmination of the laboratory sequence and the design experiences introduced throughout earlier courses is a senior design course (capstone design course), which includes a significant design project that ties together the core program, encourages creativity, explores practical aspects of engineering practice, and provides additional

ELECTRICAL ENGINEERING: THIRD AND FOURTH YEARS EARLY-STARTING STUDENTS

		SEMESTER V	SEMESTER VI	SEMESTER VII	SEMESTER VIII
PHYSICS (tracks continued)		C1403 (3) C2601 (3.5) Lab W3081 (2)	➤ Lab C1494 (3)[1] ➤ Lab C2699 (3)		
EE CORE REQUIRED COURSES		ELEN E3106 (3.5) Solid-state devices and materials	ELEN E3401 (4) Electromagnetics ELEN E3701 (3)[2] Intro. to communication systems **or** CSEE W4119 (3)[2] Computer networks		
EE REQUIRED LABS				ELEN E3043 (3) Solid state, microwave, and fiber optics lab ELEN E3399 (1) EE practice	ELEN E3390 (3)[3] Capstone design course
OTHER REQUIRED COURSES		IEOR E3658 **or** STAT 4105[4]; **and** COMS W3136 (**or** W3133, W3134, or W3137)[5] (Some of these courses *are not* offered both semesters. Students with an adequate background can take some of these courses in the sophomore year)			
ELECTIVES	EE DEPTH TECH	At least two technical electives in one depth area. The four depth areas are (a) photonics, solid-state devices, and electromagnetics; (b) circuits and electronics; (c) signals and systems; and (d) communications and networking (For details, see www.ee.columbia.edu)			
ELECTIVES	BREADTH TECH	At least two technical electives outside the chosen depth area; must be engineering courses (see www.ee.columbia.edu)			
ELECTIVES	OTHER TECH	Additional technical electives (consisting of more depth or breadth courses, or further options listed at www.ee.columbia.edu/academics/undergrad) as required to bring the total points of technical electives to 18[6]			
ELECTIVES	NONTECH	Complete 27-point requirement; see page 10 or www.seas.columbia.edu for details (administered by the advising dean)			
TOTAL POINTS[7]		16.5	17	16	18

[1] Chemistry lab (CHEM 1500) may be substituted for physics lab, although this is not generally recommended.
[2] These courses can be taken in the sophomore year if the prerequisites/corequisites are satisfied.
[3] The capstone design course provides ELEN majors with a “culminating design experience.” As such, it should be taken near the end of the program and involve a project that draws on material from a range of courses. If special arrangements are made in ELEN E3399, it is possible to use courses such as ELEN E3998, E4350, E4998, EECS E4340, or CSEE W4840 in place of ELEN E3390.
[4] SIEO W3600 and W4150 cannot generally be used to replace IEOR E3658 or STAT W4105.
[5] Students who plan to minor in Computer Science should choose COMS W3134 or W3137.
[6] The total points of technical electives is reduced to 15 if APMA E2101 has been replaced by MATH E1210 and either APMA E3101 or MATH V2010.
[7] “Total points” assumes that 20 points of nontechnical electives and other courses are included.

experience with communication skills in an engineering context. Finally, several technical electives are required, chosen to provide both breadth and depth in a specific area of interest. More detailed program objectives and outcomes are posted at www.ee.columbia.edu.

The program in electrical engineering leading to the B.S. degree is accredited by the Engineering Accreditation Commission of ABET.

There is a strong interaction between the Department of Electrical Engineering and the Departments of Computer

ELECTRICAL ENGINEERING PROGRAM: FIRST AND SECOND YEARS LATE-STARTING STUDENTS

	SEMESTER I	SEMESTER II	SEMESTER III	SEMESTER IV
MATHEMATICS	MATH V1101(3)	MATH V1102 (3)	MATH V1201 (3)	MATH V1202 (3) **and** APMA E2101 (3)[1]
PHYSICS (three tracks, choose one)	C1401 (3) → C1601 (3.5) → C2801 (4.5) →	C1402 (3) → C1602 (3.5) → C2802 (4.5) →	C1403 (3) → C2601 (3.5) → Lab W3081 (2)	Lab C1494 (3)[2] Lab C2699 (3)
CHEMISTRY	one-semester lecture (3–4) C1403 **or** C1404 **or** C3045 **or** C1604			
ELECTRICAL ENGINEERING	ELEN E1201 (3.5) either semester[3]			
ENGLISH COMPOSITION (three tracks, choose one)	C1010 (3) Z1003 (0) → Z0006 (0) →	C1010 (3) Z1003 (0) →	C1010 (3)	
REQUIRED NONTECHNICAL ELECTIVES			HUMA C1001, COCI C1101, **or** Global Core (3–4) HUMA W1121 **or** W1123 (3)	HUMA C1002, COCI C1102, **or** Global Core (3–4) ECON W1105 (4) **and** W1155 recitation (0)
COMPUTER SCIENCE	ENGI E1006 (3) any semester[4]			
PHYSICAL EDUCATION	C1001 (1)	C1002 (1)		
THE ART OF ENGINEERING	ENGI E1102 (4) either semester			

[1] APMA E2101 may be replaced by MATH E1210 and either APMA E3101 or MATH V2010.
[2] Chemistry lab (CHEM C1500) may be substituted for physics lab, although this is not generally recommended.
[3] Transfer students and 3-2 Combined Plan students who have not taken ELEN E1201 prior to the junior year are expected to have taken a roughly equivalent course when they start ELEN E3201.
[4] ENGI E1006 may not be offered every semester. See www.ee.columbia.edu for more discussion about the Computer Science sequences.

Science, Applied Physics and Applied Mathematics, Industrial Engineering and Operations Research, Physics, and Chemistry.

EE Core Curriculum

All electrical engineering (EE) students must take a set of core courses, which collectively provide the student with fundamental skills, expose him/her to the breadth of EE, and serve as a springboard for more advanced work, or for work in areas not covered in the core. These courses are shown on the charts in Undergraduate Degree Tracks. A full curriculum checklist is also posted at www.ee.columbia.edu.

Technical Electives

The 18-point technical elective requirement for the electrical engineering program consists of three components: depth, breadth, and other. A general outline is provided here, and more specific course restrictions can be found at www.ee.columbia.edu. For any course not clearly listed there, adviser approval is necessary.

The *depth* component must consist of at least 6 points of electrical engineering courses in one of four defined areas: (a) photonics, solid-state devices, and electromagnetics; (b) circuits and electronics; (c) signals and systems; and (d) communications and networking. The depth requirement provides an opportunity to pursue particular interests and exposure to the process of exploring a discipline in depth—an essential process that can be applied later to other disciplines, if desired.

The *breadth* component must consist of at least 6 additional points of engineering courses that are outside of the chosen depth area. These courses

ELECTRICAL ENGINEERING: THIRD AND FOURTH YEARS LATE-STARTING STUDENTS

	SEMESTER V	SEMESTER VI	SEMESTER VII	SEMESTER VIII
EE CORE REQUIRED COURSES	ELEN E3106 (3.5) Solid-state devices and materials ELEN E3201 (3.5) Circuit analysis ELEN E3801 (3.5) Signals and systems	CSEE W3827(3) Fund. of computer sys. ELEN E3331 (3) Electronic circuits ELEN E3401 (4) Electromagnetics ELEN E3701 (3) Intro. to communication systems **or** CSEE W4119 (3) Computer networks		
EE REQUIRED LABS	ELEN E3081 (1)[1] Circuit analysis lab ELEN E3084 (1)[1] Signals and systems lab	ELEN E3083 (1)[1] Electronic circuits lab ELEN E3082 (1)[1] Digital systems lab	ELEN E3043 (3) Solid state, microwave, and fiber optics lab ELEN E3399 (1) EE practice	ELEN E3390 (3)[2] Capstone design course
OTHER REQUIRED COURSES	IEOR E3658 **or** STAT W4105[3]; **and** COMS W3136 (**or** W3133, W3134, or W3137)[4] (Some of these courses are *not* offered both semesters)			
ELECTIVES: EE DEPTH TECH	At least two technical electives in one depth area. The four depth areas are (a) photonics, solid-state devices, and electromagnetics; (b) circuits and electronics; (c) signals and systems; and (d) communications and networking. (For details, see www.ee.columbia.edu.)			
ELECTIVES: BREADTH TECH	At least two technical electives outside the chosen depth area; must be engineering courses (see www.ee.columbia.edu)			
ELECTIVES: OTHER TECH	Additional technical electives (consisting of more depth or breadth courses, or further options listed at www.ee.columbia.edu/academics/undergrad) as required to bring the total points of technical electives to 18[5]			
ELECTIVES: NONTECH	Complete 27-point requirement; see page 10 or www.seas.columbia.edu for details (administered by the advising dean)			
TOTAL POINTS[6]	15.5	18	16	18

Note: This chart shows one possible schedule for a student who takes most of his or her major program in the final two years. Please refer to the previous chart for a recommended earlier start.

[1] If possible, these labs should be taken along with their corresponding lecture courses.

[2] The capstone design course provides ELEN majors with a "culminating design experience." As such, it should be taken near the end of the program and involve a project that draws on material from a range of courses. If special arrangements are made in ELEN E3399, it is possible to use courses such as ELEN E3998, E4350, E4998, EECS E4340, or CSEE W4840 in place of ELEN E3390.

[3] SIEO W3600 and W4150 cannot generally be used to replace IEOR E3658 or STAT W4105.

[4] Students who plan to minor in Computer Science should choose COMS W3134 or W3137.

[5] The total points of technical electives is reduced to 15 if APMA E2101 has been replaced by MATH E1210 and either APMA E3101 or MATH V2010.

[6] "Total points" assumes that 9 points of nontechnical electives are included.

can be from other departments within the School. The breadth requirement precludes overspecialization. Breadth is particularly important today, as innovation requires more and more of an interdisciplinary approach, and exposure to other fields is known to help one's creativity in one's own main field. Breadth also reduces the chance of obsolescence as technology changes.

Any remaining technical elective courses, beyond the minimum 12 points of depth and breadth, do not have to be engineering courses (except for students without *ELEN E1201* or approved transfer credit for *ELEN E1201*) but must be technical. Generally, math and science courses that do not overlap with courses used to fill other requirements are allowed.

Starting Early

The EE curriculum is designed to allow students to start their study of EE in their first year. This motivates students early and allows them to spread nontechnical requirements more evenly. It also makes evident the need for advanced math and physics concepts, and motivates the study of such concepts. Finally, it allows more time for students to take classes in a chosen depth area, or gives them more time to explore before choosing a depth area. Students can start with *ELEN E1201: Introduction to electrical engineering* in the second semester of their first year, and can continue with other core courses one semester after that, as shown in the "early-starting students" chart. It is emphasized that both the early- and late-starting sample programs shown in the charts are examples only; schedules may vary depending on student preparation and interests.

Transfer Students

Transfer students coming to Columbia as juniors with sufficient general background can complete all requirements for the B.S. degree in electrical engineering. Such students fall into one of two categories:

Plan 1: Students coming to Columbia without having taken the equivalent of *ELEN E1201* must take this course in their junior year. This requires postponing the core courses in circuits and electronics until the senior year, and thus does not allow taking electives in that area; thus, such students cannot choose circuits and electronics as a depth area.

Plan 2: This plan is for students who have taken a course equivalent to *ELEN E1201* at their school of origin, including a laboratory component. See the bulletin for a description of this course. Many pre-engineering programs and physics departments at four-year colleges offer such courses. Such students can start taking circuits at Columbia immediately, and thus can choose circuits and electronics as a depth area.

It is stressed that *ELEN E1201* or its equivalent is a key part of the EE curriculum. The preparation provided by this course is essential for a number of other core courses.

Sample programs for both Plan 1 and Plan 2 transfer students can be found at www.ee.columbia.edu.

B.S./M.S. Program

The B.S./M.S. degree program is open to a select group of undergraduate students. This double degree program makes possible the earning of both the Bachelor of Science and Master of Science degrees simultaneously. Up to 6 points may be credited to both degrees, and some graduate classes taken in the senior year may count toward the M.S. degree. Both degrees may be conferred at the same time. Interested students can find further information at www.ee.columbia.edu and can discuss options directly with their faculty adviser. Students must be admitted prior to the start of their seventh semester at Columbia Engineering. Students in the 3-2 Combined Plan undergraduate program are not eligible for admission to this program.

GRADUATE PROGRAMS

The Department of Electrical Engineering offers graduate programs leading to the degree of Master of Science (M.S.), the graduate professional degree of Electrical Engineer (E.E.), and the degrees of Doctor of Engineering Science (Eng.Sc.D.) and Doctor of Philosophy (Ph.D.). The Graduate Record Examination (General Test only) is required of all applicants except special students. An undergraduate grade-point average equivalent to B or better from an institution comparable to Columbia is expected.

Applicants who, for good reasons, are unable to submit GRE test results by the deadline date but whose undergraduate record is clearly superior may file an application without the GRE scores. An explanatory note should be added to ensure that the application will be processed even while incomplete. If the candidate's admissibility is clear, the decision may be made without the GRE scores; otherwise, it may be deferred until the scores are received.

There are no prescribed course requirements in any of the regular graduate degree programs. Students, in consultation with their faculty advisers, design their own programs, focusing on particular fields of electrical engineering. Among the fields of graduate study are microelectronics, communications and signal processing, integrated circuit and system analysis and synthesis, photonics, electromagnetic theory and applications, plasma physics, and quantum electronics.

Graduate course charts for several focus areas can be found at www.ee.columbia.edu.

Master of Science Degree

Candidates for the M.S. degree in electrical engineering must complete 30 points of credit beyond the bachelor's degree. A minimum of 15 points of credit must be at the 6000 level or higher. No credit will be allowed for undergraduate courses (3000 or lower).

At least 15 points must be in Electrical Engineering, as defined at www.ee.columbia.edu/academics/masters. Courses to be credited toward the M.S. degree can be taken only upon prior approval of a faculty adviser in the Department of Electrical Engineering. This applies to the summer session as well as the autumn and spring terms.

Certain 4000-level courses will not be credited toward the M.S. degree, and no more than 6 points of research may be taken for credit. Up to 3 points of credit for approved graduate courses outside of engineering and science may be allowed. The general school requirements listed earlier in this bulletin, such as minimum GPA, must also be satisfied. All degree requirements must be completed within five years of the beginning of the first course credited toward the degree.

More details and a checklist for adviser approvals can be found at www.ee.columbia.edu.

Professional Degree

The professional degree in electrical engineering is intended to provide

specialization beyond the level of the M.S. degree, in a focused area of electrical engineering selected to meet the professional objectives of the candidate. A minimum of 30 points of credit is required.

The prospective E.E. candidate follows a program of study formulated in consultation with, and approved by, a faculty adviser. At least three courses will be in a specific, focused area of electrical engineering, and at least two-thirds of the entire program will be in electrical engineering or computer science. No thesis is required, but the program may optionally include a seminar or project or research for which a report is produced; up to 6 points of such projects may be credited toward the degree.

The level of the courses will generally be higher than is typical of a master's degree program, although courses at the 4000 level may be included to prepare for more advanced work. A candidate is required to maintain a grade-point average of at least 3.0.

All degree requirements must be completed within five years of the beginning of the first course credited toward the degree.

Doctoral Degree

The requirements for the Ph.D. and Eng. Sc.D. degrees are identical. Both require a dissertation based on the candidate's original research, conducted under the supervision of a faculty member. The work may be theoretical or experimental or both.

Students who wish to become candidates for the doctoral degree in electrical engineering have the option of applying for admission to the Eng.Sc.D. program or the Ph.D. program. Students who elect the Eng.Sc.D. degree register in the School of Engineering and Applied Science; those who elect the Ph.D. degree register in the Graduate School of Arts and Sciences.

Doctoral candidates must obtain a minimum of 60 points of formal course credit beyond the bachelor's degree. A master's degree from an accredited institution may be accepted as equivalent to 30 points. A minimum of 30 points beyond the master's degree must be earned while in residence in the doctoral program.

More detailed information regarding the requirements for the doctoral degree may be obtained in the department office and at www.ee.columbia.edu.

Optional M.S. Concentrations

Students in the electrical engineering M.S. program often choose to use some of their electives to focus on a particular field. Students may pick one of a number of optional, formal concentration templates or design their own M.S. program in consultation with an adviser. These concentrations are not degree requirements. They represent suggestions from the faculty as to how one might fill one's programs so as to focus on a particular area of interest. Students may wish to follow these suggestions, but they need not. The degree requirements are quite flexible and are listed in the Master of Science Degree section, above. All students, whether following a formal concentration template or not, are expected to include breadth in their program. Not all of the elective courses listed here are offered every year. For the latest information on available courses, visit the Electrical

Engineering home page at www.ee.columbia.edu.

Concentration in Multimedia Networking

Advisers: Professors Henning Schulzrinne, Predrag Jelenkovic

1. Satisfy M.S. degree requirements.
2. Both *ELEN E6761: Computer communication networks, I* and *ELEN E6950: Wireless and mobile networking, I.*
3. Either *COMS W4118: Operating systems* or *COMS W4111: Database systems.*
4. *COMS E6181: Advanced Internet services* or *ELEN E6776: Topic: content distribution networks.*

With an adviser's approval, any of the courses above can be replaced by the following closely related subjects: *CSEE E4140: Networking laboratory; CSEE W4119: Computer networks; COMS W4180: Network security; ELEN E6762: Computer communication networks, II; ELEN E6850: Visual information systems; ELEN E6951: Wireless and mobile networking, II.*

Concentration in Telecommunications Engineering

Advisers: Professors Henning Schulzrinne, Pedrag Jelenkovic, Ed Coffman, Nicholas Maxemchuk, Gil Zussman

1. Satisfy M.S. degree requirements.
2. One basic hardware or software course such as: *EECS E4321: Digital VLSI circuits; ELEN E4411: Fundamentals of photonics; COMS W4118: Operating systems, I; COMS W4111: Database systems.*
3. One basic systems course such as: *ELEN E4702: Communication theory; ELEN E4703: Wireless communications; CSEE W4119: Computer networks; ELEN E6761: Computer communication networks, I.*
4. At least two approved courses from a focus area such as Signal/Image Processing and Telecommunications/Multimedia Networks.

Concentration in Lightwave (Photonics) Engineering

Advisers: Professors Keren Bergman, Paul Diament, Richard Osgood, Amiya Sen, Tony Heinz, Ioannis (John) Kymissis

1. Satisfy M.S. degree requirements.
2. Take both *ELEN E4411: Fundamentals of photonics* and *ELEN E6412: Lightware devices* (or an E&M course, such as *APPH E4300: Applied electrodynamics* or *PHYS G6092: Electromagnetic theory).*
3. One more device/circuits/photonics course such as: *ELEN E6413: Lightwave systems; ELEN E6414: Photonic integrated circuits; ELEN E4314: Communication circuits; ELEN E4488: Optical systems; ELEN E6488: Optical interconnects and interconnection networks; ELEN E4193: Modern display science and technology.*
4. At least two additional approved courses in photonics or a related area. Options also include courses outside EE such as *APPH E4090: Nanotechnology; APPH E4100: Quantum physics of matter; APPH E4110: Modern optics; CHAP E4120: Statistical mechanics; APPH E4112: Laser physics; APPH E4130: Physics of solar energy; APPH E6081: Solid state physics, I; APPH E6082: Solid state physics, II; APPH E6091: Magnetism and magnetic materials; APPH E6110: Laser interactions with matter; MSAE E4202: Thermodynamics and reactions in solids; MSAE E4206: Electronic and magnetic properties of solids; MSAE E4207: Lattice vibrations and crystal defects; MSAE E6120: Grain boundaries and interfaces; MSAE E6220: Crystal physics; MSAE E6229: Energy and particle beam processing of materials; MSAE E6225: Techniques in X-ray and neutron diffraction.*

Concentration in Wireless and Mobile Communications

Adviser: Professors Gil Zussman, Predrag Jelenkovic, Xiaodong Wang

1. Satisfy M.S. degree requirements.
2. One basic circuits course such as: *ELEN E4312: Analog electric circuits; ELEN E4314: Communication circuits; ELEN E6314: Advanced communication circuits; ELEN E6312: Advanced analog ICs.*
3. Two communications or networking courses such as: *CSEE W4119: Computer networks; ELEN E4702: Digital communications; ELEN E4703: Wireless communications; ELEN E6711: Stochastic signals and noise; ELEN E4810: Digital signal processing; ELEN E6950: Wireless and mobile networking, I; ELEN E6951: Wireless and mobile networking, II; ELEN E6761: Computer communication networks, I; ELEN E6712: Communication theory; ELEN E6713: Topics in communications; ELEN E6717: Information theory; ELEN E677x: Topics in telecommunication networks.*
4. At least two additional approved courses in wireless communications or a related area.

Concentration in Integrated Circuits and Systems

Advisers: Professors Peter Kinget, Harish Krishnaswamy, Mingoo Seok, Kenneth Shepard, Yannis Tsividis, Charles Zukowski

1. Satisfy M.S. degree requirements.
2. One digital course from: *EECS E4321: Digital VLSI circuits* or *EECS E6321: Advanced digital electronic circuits.*
3. One analog course from: *ELEN E4312: Analog electronic circuits; ELEN E6312: Advanced analog integrated circuits; ELEN E6316: Analog circuits and systems in VLSI; ELEN E4314: Communication circuits; ELEN E6314: Advanced communication circuits; ELEN E6320: Millimeter-wave IC design.*
4. Two additional courses such as: Other courses from 2. and 3.; *ELEN E6350: VLSI design laboratory; ELEN E6304: Topics in electronic circuits; ELEN E6318: Microwave circuit design; ELEN E9303: Seminar in electronic circuits.*
5. At least one additional approved course in integrated circuits and systems or a related area.

Concentration in Microelectronic Devices

Advisers: Professors Wen Wang, Richard Osgood, Ioannis (John) Kymissis

1. Satisfy M.S. degree requirements.
2. One basic course such as: *ELEN E4301: Introduction to semiconductor devices* or *ELEN E4411: Fundamentals of photonics.*
3. One advanced course such as: *ELEN E4193: Modern display science and technology; ELEN E4944: Principles of device microfabrication; ELEN E4503: Sensors, actuators, and electromechanical systems; ELEN E6151: Surface physics and analysis of electronic materials; ELEN E6331: Principles of semiconductor physics, I; ELEN E6332: Principles of semiconductor physics, II; ELEN E6333: Semiconductor device physics; ELEN E6945: Nanoscale fabrication and devices.*
4. At least two other approved courses in devices or a related area. Options also include courses outside EE such as *APPH E4090: Nanotechnology; APPH E4100: Quantum physics of matter; APPH E4110: Modern optics; CHAP E4120: Statistical mechanics; APPH E4112: Laser physics; APPH E4130: Physics of solar energy; APPH E6081: Solid state physics, I; APPH E6082: Solid state physics, II; APPH E6091: Magnetism and magnetic materials; APPH E6110: Laser interactions with matter; MSAE E4202: Thermodynamics and reactions in solids; MSAE E4206: Electronic and magnetic properties of solids; MSAE E4207: Lattice vibrations and crystal defects; MSAE E6120: Grain boundaries and interfaces; MSAE E6220: Crystal physics; MSAE E6229: Energy and particle beam processing of materials; MSAE E6225: Techniques in X-ray and neutron diffraction.*

Concentration in Systems Biology and Neuroengineering

Advisers: Professors Dimitris Anastassiou, Christine Fleming, Pedrag Jelenkovic, Aurel Lazar, Nima Mesgarani, Kenneth Shepard, Xiaodong Wang, Charles Zukowski

1. Satisfy M.S. degree requirements.
2. Take both *ECBM E4060: Introduction to genomic information science and technology* and *BMEB W4020: Computational neuroscience, I: circuits in the brain*
3. Take at least one course from *BMEE E4030: Neural control engineering; CBMF W4761: Computational genomics; BIST P8139: Theoretical genetic modeling* (Biostatistics); *ELEN E6010: Systems biology*; *EEBM E6020: Methods in computational neuroscience*; *BMEE E6030: Neural modeling and neuroengineering*; *APMA E4400: Introduction to biophysical modeling*; *CHEN E4700: Principles of genomic technologies*; *CHEN E4760: Genomics sequencing lab; ELEN E4312: Analog electronic circuits*.
4. Take at least one course from *ELEN E608x: Topics in systems biology; ELEN E6717: Information theory; ELEN E6201: Linear systems theory; EEME E6601: Introduction to control theory; ELEN E6711: Stochastic models in information systems; ELEN E6860: Advanced digital signal processing; EEBM E6090: Topics in computational neuroscience and neuroengineering; ELEN E6261: Computational methods of circuit analysis.*

COURSES IN ELECTRICAL ENGINEERING

ELEN E1101x or y The digital information age
3 pts. Lect: 3. Professor Vallancourt.
An introduction to information transmission and storage, including technological issues. Binary numbers; elementary computer logic; digital speech and image coding; basics of compact disks, telephones, modems, faxes, UPC bar codes, and the World Wide Web. Projects include implementing simple digital logic systems and Web pages. Intended primarily for students outside the School of Engineering and Applied Science. The only prerequisite is a working knowledge of elementary algebra.

ELEN E1201x and y Introduction to electrical engineering
3.5 pts. Lect: 3. Lab:1. Professor Vallancourt.
Prerequisite: MATH V1101. Basic concepts of electrical engineering. Exploration of selected topics and their application. Electrical variables, circuit laws, nonlinear and linear elements, ideal and real sources, transducers, operational amplifiers in simple circuits, external behavior of diodes and transistors, first order RC and RL circuits. Digital representation of a signal, digital logic gates, flip-flops. A lab is an integral part of the course. Required of electrical engineering and computer engineering majors.

ELEN E3043x Solid state, microwave and fiber optics laboratory
3 pts. Lect: 1. Lab: 6. Professor W. Wang.
Prerequisites: ELEN E3106 and ELEN E3401. Optical electronics and communications. Microwave circuits. Physical electronics.

ECBM E3060x Introduction to genomic information science and technology
3 pts. Lect: 3. Professor Anastassiou.
Introduction to the information system paradigm of molecular biology. Representation, organization, structure, function and manipulation of the biomolecular sequences of nucleic acids and proteins. The role of enzymes and gene regulatory elements in natural biological functions as well as in biotechnology and genetic engineering. Recombination and other macromolecular processes viewed as mathematical operations with simulation and visualization using simple computer programming. This course shares lectures with ECBM E4060, but the work requirements differ somewhat.

ELEN E3081x Circuit analysis laboratory
1 pt. Lab: 3. Professor Zukowski.
Prerequisite: ELEN E1201 or equivalent. Corequisite: ELEN E3201. Companion lab course for ELEN E3201. Experiments cover such topics as: use of measurement instruments; HSPICE simulation; basic network theorems; linearization of nonlinear circuits using negative feedback; op-amp circuits; integrators; second order RLC circuits. The lab generally meets on alternate weeks.

ELEN E3082y Digital systems laboratory
1 pt. Lab: 3. Professor Shepard.
Corequisite: CSEE W3827. Recommended preparation: ELEN E1201 or equivalent. Companion lab course for CSEE W3827. Experiments cover such topics as logic gates; flip-flops; shift registers; counters; combinational logic circuits; sequential logic circuits; programmable logic devices. The lab generally meets on alternate weeks.

ELEN E3083y Electronic circuits laboratory
1 pt. Lab: 3. Professor Vallancourt.
Prerequisite: ELEN E3081. Corequisite: ELEN E3331. Companion lab course for ELEN E3331. Experiments cover such topics as macromodeling of nonidealities of opamps using SPICE; Schmitt triggers and astable multivibrations using opamps and diodes; logic inverters and amplifiers using bipolar junction transistors; logic inverters and ring oscillators using MOSFETs; filter design using op-amps. The lab generally meets on alternate weeks.

ELEN E3084x Signals and systems laboratory
1 pt. Lab: 3. Professor X. Wang.
Corequisite: ELEN E3801. Companion lab course for ELEN E3801. Experiments cover topics such as: introduction and use of MATLAB for numerical and symbolic calculations; linearity and time invariance; continuous-time convolution; Fourier-series expansion and signal

reconstruction; impulse response and transfer function; forced response. The lab generally meets on alternate weeks.

ELEN E3106x Solid-state devices and materials
3.5 pts. Lect: 3. Recit: 1. Professor Kymissis.
Prerequisite: MATH V1201 or equivalent. Corequisite: PHYS C1403 or PHYS C2601 or equivalent. Crystal structure and energy band theory of solids. Carrier concentration and transport in semiconductors. P-n junction and junction transistors. Semiconductor surface and MOS transistors. Optical effects and optoelectronic devices.

ELEN E3201x Circuit analysis
3.5 pts. Lect: 3. Recit: 1. Professor Zukowski.
Prerequisite: ELEN E1201 or equivalent. Corequisite: MATH V1201. A course on analysis of linear and nonlinear circuits and their applications. Formulation of circuit equations. Network theorems. Transient response of first and second order circuits. Sinusoidal steady state-analysis. Frequency response of linear circuits. Poles and zeros. Bode plots. Two-port networks.

ELEN E3331y Electronic circuits
3 pts. Lect: 3. Professor Vallancourt.
Prerequisites: ELEN E3201. Operational amplifier circuits. Diodes and diode circuits. MOS and bipolar junction transistors. Biasing techniques. Small-signal models. Single-stage transistor amplifiers. Analysis and design of CMOS logic gates. A/D and D/A converters.

ELEN E3390y Electronic circuit design laboratory
3 pts. Lab: 6. Professor Vallancourt.
Prerequisites: ELEN E3082, E3083, E3331, E3401, E3801. Advanced circuit design laboratory. Students work in teams to specify, design, implement and test an engineering prototype. The work involves technical as well as non-technical considerations, such as manufacturability, impact on the environment, and economics. The projects may change from year to year.

ELEN E3399x Electrical engineering practice
1 pt. Professor Vallancourt.
Design project planning, written and oral technical communication, practical aspects of engineering as a profession, such as career development and societal and environmental impact. Generally taken senior year.

ELEN E3401y Electromagnetics
4 pts. Lect: 3. Professor Diament.
Prerequisite: MATH V1201, PHYS C1402 or PHYS C1602, or equivalents. Basic field concepts. Interaction of time-varying electromagnetic fields. Field calculation of lumped circuit parameters. Transition from electrostatic to quasistatic and electromagnetic regimes. Transmission lines. Energy transfer, dissipation, and storage. Waveguides. Radiation.

EEME E3601x Classical control systems
3 pts. Lect: 3. Professor Longman.
Prerequisite: MATH E1210. Analysis and design of feedback control systems. Transfer functions; block diagrams; proportional, rate, and integral controllers; hardware; implementation. Routh stability criterion, root locus, Bode and Nyquist plots, compensation techniques.

ELEN E3701y Introduction to communication systems
3 pts. Lect: 3. Professor Kalet.
Prerequisite: ELEN E3801. Corequisite: IEOR E3658. A basic course in communication theory, stressing modern digital communication systems. Nyquist sampling, PAM and PCM/DPCM systems, time division multipliexing, high frequency digital (ASK, OOK, FSK, PSK) systems, and AM and FM systems. An introduction to noise processes, detecting signals in the presence of noise, Shannon's theorem on channel capacity, and elements of coding theory.

ELEN E3801x Signals and systems
3.5 pts. Lect: 3. Professor X. Wang.
Corequisite: MATH V1201. Modeling, description, and classification of signals and systems. Continuous-time systems. Time domain analysis, convolution. Frequency domain analysis, transfer functions. Fourier series. Fourier and Laplace transforms. Discrete-time systems and the Z transform.

CSEE W3827x and y Fundamentals of computer systems
3 pts. Lect: 3. Professors Kim and Rubenstein.
Prerequisites: An introductory programming course. Fundamentals of computer organization and digital logic. Boolean algebra, Karnaugh maps, basic gates and components, flipflops and latches, counters and state machines, basics of combinational and sequential digital design. Assembly language, instruction sets, ALUs, single-cycle and multi-cycle processor design, introduction to pipelined processors, caches, and virtual memory.

ELEN E3998x and y Projects in electrical engineering
0 to 3 pts.
Prerequisite: Requires approval by a faculty member who agrees to supervise the work. May be repeated for credit, but no more than 3 total points may be used for degree credit. Independent project involving laboratory work, computer programming, analytical investigation, or engineering design.

BMEB W4020x Computational neuroscience: circuits in the brain
3 pts. Lect: 3. Professor Lazar.
Prerequisite: ELEN E3801 or BIOL W3004. The biophysics of computation: modeling biological neurons, the Hodgkin-Huxley neuron, modeling channel conductances and synapses as memristive systems, bursting neurons and central pattern generators, I/O equivalence and spiking neuron models. Information representation and neural encoding: stimulus representation with time encoding machines, the geometry of time encoding, encoding with neural circuits with feedback, population time encoding machines. Dendritic computation: elements of spike processing and neural computation, synaptic plasticity and learning algorithms, unsupervised learning and spike time-dependent plasticity, basic dendritic integration. Projects in MATLAB.

BMEE E4030 y Neural control engineering
3 pts. Lect: 3.
Prerequisite: ELEN E3801. Topics include: Basic cell biophysics, active conductance and the Hodgkin-Huxley model, simple neuron models, ion channel models and synaptic models, statistical models of spike generation, Wilson-Cowan model of cortex, large-scale electrophysiological recording methods, sensorimotor integration and optimal state estimation, operant conditioning of neural activity, nonlinear modeling of neural systems, sensory systems: visual pathway and somatosensory pathway, neural encoding model: spike triggered average (STA) and spike triggered covariance (STC) analysis, neuronal response to electrical micro-stimulation, DBS for Parkinson's disease treatment, motor neural prostheses, and sensory neural prostheses.

ECBM E4060x Introduction to genomic information science and technology
3 pts. Lect: 3. Professor Anastassiou.
Introduction to the information system paradigm of molecular biology. Representation, organization, structure, function and manipulation of the biomolecular sequences of nucleic acids and proteins. The role of enzymes and gene regulatory elements in natural biological functions as well as in biotechnology and genetic engineering. Recombination and other macromolecular processes viewed as mathematical operations with simulation and visualization using simple computer programming. This course shares lectures with ECBM E3060, but the work requirements differ somewhat.

CSEE W4119x and y Computer networks
3 pts. Lect: 3. Professor Misra.
Corequisite: IEOR E3658 or SIEO W3600 or equivalents. Introduction to computer networks and the technical foundations of the Internet, including applications, protocols, local area networks, algorithms for routing and congestion control, security, elementary performance evaluation. Several written and programming assignments required.

CSEE W4140x or y Networking laboratory
3 pts. Lect: 3. Professor Zussman.
Prerequisite: CSEE W4119 or equivalent. In this course, students learn how to put "principles into practice," in a hands-on-networking lab course. The technologies and protocols of the Internet are covered, using equipment currently available to large Internet service providers such as CISCO routers and end-systems. A set of laboratory experiments provides hands-on experience with engineering wide-area networks and familiarizes students with the Internet Protocol (IP), Address Resolution Protocol (ARP), Internet Control Message Protocol (ICMP), User Datagram Protocol (UDP) and Transmission Control Protocol (TCP), the Domain Name System (DNS), routing protocols (RIP, OSPF, BGP), network management protocols (SNMP), and application-level protocols (FTP, TELNET, SMTP).

ELEN E4193x or y Modern display science and technology
3 pts. Lect: 3. Professor Kymissis.
Prerequisites: Linear algebra, differential equations, and basic semiconductor physics. Introduction to modern display systems in an engineering context. The basis for visual perception, image representation, color space, metrics of illumination. Physics of luminescence, propagation and manipulation of light in anisotropic media, emissive displays, and spatial light modulators. Fundamentals of display addressing, the Alt-Pleshko theorem, multiple line addressing. Large area electronics, fabrication, and device integration of commercially important display types. A series of short laboratories will reinforce material from the lectures. Enrollment may be limited.

ELEN E4301y Introduction to semiconductor devices
3 pts. Lect: 3. Professor Laibowitz.
Prerequisite: ELEN E3106 or equivalent. Semiconductor physics. Carrier injection and recombination. P-n junction and diodes: Schottky barrier and heterojunctions, solar cells and light-emitting diodes. Junction and MOS field-effect transistors, bipolar transistors. Tunneling and charge-transfer devices.

ELEN E4312x Analog electronic circuits
3 pts. Lect: 3. Professor Tsividis.
Prerequisites: ELEN E3331 and ELEN E3801. Differential and multistage amplifiers; small-signal analysis; biasing techniques; frequency response; negative feedback; stability criteria; frequency compensation techniques. Analog layout techniques. An extensive design project is an integral part of the course.

ELEN E4314y Communication circuits
3 pts. Lect: 3. Professor Tsividis.
Prerequisite: ELEN E4312. Principles of electronic circuits used in the generation, transmission, and reception of signal waveforms, as used in analog and digital communication systems. Nonlinearity and distortion; power amplifiers; tuned amplifiers; oscillators; multipliers and mixers; modulators and demodulators; phase-locked loops. An extensive design project is an integral part of the course.

EECS E4321x Digital VLSI circuits
3 pts. Lect: 3. Professor Shepard.
Recommended preparation: ELEN E3331, CSEE W3827, and ELEN E3106. Design and analysis of high speed logic and memory. Digital CMOS and BiCMOS device modeling. Integrated circuit fabrication and layout. Interconnect and parasitic elements. Static and dynamic techniques. Worst-case design. Heat removal and I/O. Yield and circuit reliability. Logic gates, pass logic, latches, PLAs, ROMs, RAMs, receivers, drivers, repeaters, sense amplifiers.

EECS E4340x Computer hardware design
3 pts. Lect: 2. Lab: 3. Professor Sethumadhavan.
Prerequisites: ELEN E3331 and CSEE W3827. Practical aspects of computer hardware design through the implementation, simulation, and prototyping of a PDP-8 processor. High-level and assembly languages, I/O, interrupts, datapath and control design, pipelining, busses, memory architecture. Programmable logic and hardware prototyping with FPGAs. Fundamentals of VHDL for register-transfer level design. Testing and validation of hardware. Hands-on use of industry CAD tools for simulation and synthesis.

BMEE E4400x Wavelet applications in biomedical image and signal processing
3 pts. Lect: 3.
Prerequisites: APMA E2101 or APMA E3101 or equivalent. An introduction to methods of wavelet analysis and processing techniques for the quantification of biomedical images and signals. Topics include: frames and overcomplete representations, multiresolution algorithms for denoising and image restoration, multiscale texture segmentation and classification methods for computer aided diagnosis.

ELEN E4401x Wave transmission and fiber optics
3 pts. Lect: 3. Professor Diament.
Prerequisite: ELEN E3401 or equivalent. Waves and Maxwell's equations. Field energetics, dispersion, complex power. Waves in dielectrics and in conductors. Reflection and refraction. Oblique incidence and total internal reflection. Transmission lines and conducting waveguides. Planar and circular dielectric waveguides; integrated optics and optical fibers. Hybrid and LP modes. Graded-index fibers. Mode coupling; wave launching.

ELEN E4411x Fundamentals of photonics
3 pts. Lect: 3. Professor Osgood.
Prerequisite: ELEN E3401 or equivalent. Planar resonators. Photons and photon streams. Photons and atoms: energy levels and band structure; interactions of photons with matter; absorption, stimulated and spontaneous emission; thermal light, luminescence light. Laser amplifiers: gain, saturation, and phase shift; rate equations; pumping. Lasers: theory of oscillation; laser output characteristics. Photons in semiconductors: generation, recombination, and injection; heterostructures; absorption and gain coefficients. Semiconductor photon sources: LEDs; semiconductor optical amplifiers; homojunction and heterojunction laser diodes. Semiconductor photon detectors: p-n, p-i-n, and heterostructure photo diodes; avalanche photodiodes.

ELEN E4488x Optical systems
3 pts. Lect: 3. Professor Bergman.
Prerequisite: ELEN E3401 or equivalent. Introduction to optical systems based on physical design and engineering principles. Fundamental geometrical and wave optics with specific emphasis on developing analytical and numerical tools used in optical engineering design. Focus on applications that employ optical systems and networks, including examples in holographic imaging, tomography, Fourier imaging, confocal microscopy, optical signal processing, fiber optic communication systems, optical interconnects and networks.

ELEN E4501x Electromagnetic devices and energy conversion
3 pts. Lect: 3. Professor Sen.
Prerequisite: ELEN E3401. Linear and nonlinear magnetic circuits. Electric and magnetic energy storage, loss, and transfer. Circuit behavior of energy storage and transfer devices. Field theory of moving bodies. Dynamical equations of an electromechanical system. Electromechanical and thermo-electric sensors and actuators. Rotating electric energy converters. Superconductivity and applications.

ELEN E4503x Sensors, actuators and electromechanical systems
3 pts. Lect: 3.
Prerequisites: ELEN E3201 and ELEN E3401, or equivalents. Electromagnetic energy storage, loss, and transfer. Dynamics of electromechanical systems. Linearization of nonlinear coupled dynamical equations and equivalent circuits. Electromechanical actuators: acoustic, IC processed micromachines. Electromechanical sensors: acoustic, pressure, and acceleration. Thermal sensors: polysilicon thermopiles and bipolar transistor temperature sensors. Electro-optic sensors: visible light, infrared, and X-ray.

ELEN E4510x or y Solar energy and smart grid power systems
3 pts. Lect: 3. Professors Kymissis and Schwartz.
Prerequisite: Background in circuits. Inorganic solar cell semiconductor physics. Single and

tandem junction design. Measures of spectral and energy efficiency. Introduction to organic solar cells and thin film inorganic cells. Batteries and other energy storage systems. Introduction to legacy power networks: Single phase equivalents to three-phase networks. Reactive and real power. Equivalent circuits of synchronous machines, transformers, and transmission lines. Smart grid technology: Control and management of distributed solar energy and other intermittent renewable power sources connected to legacy power networks. Microgrid concept. "Small world" networks and fault management. Communication over power lines. Smart metering.

ELEN E4511x or y Power systems analysis and control
3 pts. Lect: 3. Professor Lavaei.
Prerequisites: ELEN E3201 and ELEN E3401, or equivalents, or instructor's permission. Modeling of power networks, steady-state and transient behaviors, control and optimization, electricity market, and smart grid.

EEME E4601y Digital control systems
3 pts. Lect: 3. Professor Longman.
Prerequisite: ELEN E3801 or EEME E3601, or equivalent. Real-time control using digital computers. Solving scalar and state-space difference equations. Discrete equivalents of continuous systems fed by holds. Z-transfer functions. Creating closed-loop difference equation models by Z-transform and state variable approaches. The Nyquist frequency and sample rate selection. Classical- and modern-based digital control laws. Digital system identification.

EEOR E4650x or y Convex optimization for electrical engineering
3 pts. Lect: 3. Professor Lavaei.
Prerequisite: ELEN E3801 or instructor's permission. Theory of convex optimization; numerical algorithms; applications in circuits, communications, control, signal processing and power systems.

ELEN E4702x or y Digital communications
3 pts. Lect: 3. Professor Cvijetic.
Prerequisite: ELEN E3701 or equivalent. Digital communications for both point-to-point and switched applications is further developed. Optimum receiver structures and transmitter signal shaping for both binary and M-ary signal transmission. An introduction to block codes and convolutional codes, with application to space communications.

ELEN E4703y Wireless communications
3 pts. Lect: 3. Professor Diament.
Prerequisite: ELEN E3701 or equivalent. Wireless communication systems. System design fundamentals. Trunking theory. Mobile radio propagation. Reflection of radio waves. Fading and multipath. Modulation techniques; signal space; probability of error, spread spectrum. Diversity. Multiple access.

ELEN E4810x Digital signal processing
3 pts. Lect: 3. Professor Ellis.
Prerequisite: ELEN E3801. Digital filtering in time and frequency domain, including properties of discrete-time signals and systems, sampling theory, transform analysis, system structures, IIR and FIR filter design techniques, the Discrete Fourier Transform, Fast Fourier Transforms.

ELEN E4815y Random signals and noise
3 pts. Lect: 3.
Prerequisite: IEOR E3658 or equivalent. Characterization of stochastic processes as models of signals and noise; stationarity, ergodicity, correlation functions, and power spectra. Gaussian processes as models of noise in linear and nonlinear systems; linear and nonlinear transformations of random processes; orthogonal series representations. Applications to circuits and devices, to communication, control, filtering, and prediction.

CSEE W4823x or y Advanced logic design
3 pts. Lect: 3. Professor Nowick.
Prerequisite: CSEE W3827 or equivalent. An introduction to modern digital system design. Advanced topics in digital logic: controller synthesis (Mealy and Moore machines); adders and multipliers; structured logic blocks (PLDs, PALs, ROMs); iterative circuits. Modern design methodology: register transfer level modeling (RTL); algorithmic state machines (ASMs); introduction to hardware description languages (VHDL or Verilog); system-level modeling and simulation; design examples.

CSEE W4824x or y Computer architecture
3 pts. Lect: 3. Professor Carloni.
Prerequisite: CSEE W3827 or equivalent. Focuses on advanced topics in modern computer architecture, illustrated by recent case studies. Fundamentals of quantitative analysis. Pipelined, out-of-order, and speculative execution. Superscalar, VLIW and vector processors. Embedded processors. Memory hierarchy design. Multiprocessors and thread-level parallelism. Synchronization and cache coherence protocols. Interconnection networks.

ELEN E4830y Digital image processing
3 pts. Lect: 3.
Introduction to the mathematical tools and algorithmic implementation for representation and processing of digital pictures, videos, and visual sensory data. Image representation, filtering, transform, quality enhancement, restoration, feature extraction, object segmentation, motion analysis, classification, and coding for data compression. A series of programming assignments reinforces material from the lectures.

ELEN E4835 Introduction to adaptive signal representations
3 pts. Lect: 2. Professor Wright.
Prerequisites: Linear algebra (APMA E3101, MATH V2010, or equivalent), probability (IEOR E3658 or equivalent), and signals and systems (ELEN E3801), or instructor's permission. Introduces numerical tools for adaptive processing of signals. Signal representations, sparsity in overcomplete bases. Techniques for sparse recovery, applications to inpainting and denoising. Adaptive representations: Principal Component Analysis, clustering and vector quantization, dictionary learning. Source separation: Independent Component Analysis and matrix factorizations. Signal classification: support vector machines and boosting, learning with invariances. Hashing and signal retrieval. Case studies from image processing, audio, multimedia.

CSEE W4840y Embedded systems
3 pts. Lect: 3.
Prerequisite: CSEE W4823 or equivalent. Embedded system design and implementation combining hardware and software. I/O, interfacing, and peripherals. Weekly laboratory sessions and term project on design of a microprocessor-based embedded system including at least one custom peripheral. Knowledge of C programming and digital logic required.

ELEN E4896y Music signal processing
3 pts. Lect: 3.
Prerequisite: ELEN E3801, E4810, or the equivalent. An investigation of the applications of signal processing to music audio, spanning the synthesis of musical sounds (including frequency modulation [FM], additive sinusoidal synthesis, and linear predictive coding [LPC]), the modification of real and synthetic sounds (including reverberation and time/pitch scaling), and the analysis of music audio to extract musical information (including pitch tracking, chord transcription, and music matching). Emphasis on practical, hands-on experimentation, with a wide range of software implementations introduced and modified within the class.

ELEN E4944x or y Principles of device microfabrication
3 pts. Lect: 3. Professor Yardley.
Science and technology of conventional and advanced microfabrication techniques for electronics, integrated and discrete components. Topics include diffusion; ion implantation, thin-film growth including oxides and metals, molecular beam and liquid-phase epitaxy; optical and advanced lithography; and plasma and wet etching.

ELEN E4998x or y Intermediate projects in electrical engineering
0–3 pts.
Prerequisite: Requires approval by a faculty member who agrees to supervise the work. May be repeated for credit, but no more than 3 total points may be used for degree credit. Substantial independent project involving laboratory work, computer programming, analytical investigation, or engineering design.

ELEN E6001x-E6002y Advanced projects in electrical engineering
1–4 pts. Members of the faculty.
Prerequisite: Requires approval by a faculty member who agrees to supervise the work. May be repeated for up to 6 points of credit. Graduate-level projects in various areas of electrical engineering and computer science. In consultation with an instructor, each student designs his or her project depending on the student's previous training and experience. Students should consult with a professor in their area for detailed arrangements no later than the last day of registration.

ELEN E6010y Systems biology: design principles for biological circuits
4.5 pts. Lect: 3.
Prerequisite: ECBM E4060 or instructor's permission. Beyond bioinformatics, cells as systems. Metabolic networks, transcription regulatory networks, signaling networks. Deterministic and stochastic kinetics. Mathematical representation of reconstructed networks. Network motifs. Signal transduction and neuronal networks. Robustness. Bacterial chemotaxis and patterning in fruit fly development. Kinetic proofreading. Optimal gene circuit design. Rules for gene regulation. Random networks and multiple time scales. Biological information processing. Numerical and simulation techniques. Major project(s) in MATLAB.

EEBM E6020y Methods of computational neuroscience
4.5 pts. Lect: 3.
Prerequisite: BMEB W4020 or instructor's permission. Formal methods in computational neuroscience including methods of signal processing, communications theory, information theory, systems and control, system identification and machine learning. Molecular models of transduction pathways. Robust adaptation and integral feedback. Stimulus representation and groups. Stochastic and dynamical systems models of spike generation. Neural diversity and ensemble encoding. Time encoding machines and neural codes. Stimulus recovery with time decoding machines. MIMO models of neural computation. Synaptic plasticity and learning algorithms. Major project(s) in MATLAB.

BMEE E6030x Neural modeling and neuroengineering
3 pts. Lect: 3. Professor Sajda.
Prerequisites: ELEN E3801 and either APMA E2101 or APMA E3101, or equivalent, or instructor's permission. Engineering perspective on the study of multiple levels of brain organization, from single neurons to cortical modules and systems. Mathematical models of spiking neurons, neural dynamics, neural coding, and biologically-based computational learning. Architectures and learning principles underlying both artificial and biological neural networks. Computational models of cortical processing, with an emphasis on the visual system. Applications of principles in neuroengineering; neural prostheses, neuromorphic systems and biomimetics. Course will include a computer simulation laboratory.

ELEN E6080–6089x or y Topics in systems biology
3 pts. Lect: 2.
Prerequisite: Instructor's permission. Selected advanced topics in systems biology. Content varies from year to year, and different topics rotate through the course numbers 6080 to 6089.

EEBM E6090–6099x or y Topics in computational neuroscience and neuroengineering
3 pts. Lect: 2.
Prerequisite: Instructor's permission. Selected advanced topics in computational neuroscience and neuroengineering. Content varies from year to year, and different topics rotate through the course numbers 6090 to 6099.

CSEE E6180x or y Modeling and performance evaluation
3 pts. Lect: 2.
Prerequisites: COMS W4118 and SIEO W4150 or permission of the instructor. Introduction to queuing analysis and simulation techniques. Evaluation of time-sharing and multiprocessor systems. Topics include priority queuing, buffer storage, and disk access, interference and bus contention problems, and modeling of program behaviors.

ELEN E6201x Linear system theory
3 pts. Lect: 3. Professor Fishler.
Prerequisites: ELEN E3801 and APMA E3101, or equivalents. Abstract objects, the concepts of state. Definition and properties of linear systems. Characterization of linear continuous-time and discrete-time, fixed, and time-varying systems. State-space description; fundamental matrix, calculation by computer and matrix methods. Modes in linear systems. Adjoint systems. Controllability and observability. Canonical forms and decompositions. State estimators. Lyapunov's method and stability.

ELEN E6312y Advanced analog integrated circuits
3 pts. Lect: 2.
Prerequisite: ELEN E4312. Integrated circuit device characteristics and models; temperature- and supply-independent biasing; IC operational amplifier analysis and design and their applications; feedback amplifiers, stability and frequency compensation techniques; noise in circuits and low-noise design; mismatch in circuits and low-offset design. Computer-aided analysis techniques are used in homework or a design project.

ELEN E6314x Advanced communication circuits
3 pts. Lect: 2.
Prerequisites: ELEN E4314 and ELEN E6312. Overview of communication systems, modulation and detection schemes. Receiver and transmitter architectures. Noise, sensitivity, and dynamic range. Nonlinearity and distortion. Low-noise RF amplifiers, mixers, and oscillators. Phase-locked loops and frequency synthesizers. Typical applications discussed include wireless RF transceivers or data links. Computer-aided analysis techniques are used in homework(s) or a design project.

ELEN E6316y Analog systems in VLSI
3 pts. Lect: 3.
Prerequisite: ELEN E4312. Analog-digital interfaces in very large scale integrated circuits. Precision sampling; A/D and D/A converter architectures; continuous-time and switched capacitor filters; system considerations. A design project is an integral part of this course.

ELEN E6318x or y Microwave circuit design
3 pts. Lect: 3.
Prerequisites: ELEN E3331 and E3401, or equivalents. Introduction to microwave engineering and microwave circuit design. Review of transmission lines. Smith chart, S-parameters, microwave impedance matching, transformation and power combining networks, active and passive microwave devices, S-parameter-based design of RF and microwave amplifiers. A microwave circuit design project (using microwave CAD) is an integral part of the course.

ELEN E6320x or y Millimeter-wave IC design
3 pts. Lect: 3. Professor Krishnaswamy.
Prerequisites: ELEN E3401 or equivalent, ELEN E4314 and E6312. Principles behind the implementation of millimeter-wave (30GHz-300GHz) wireless circuits and systems in silicon-based technologies. Silicon-based active and passive devices for millimeter-wave operation, millimeter-wave low-noise amplifiers, power amplifiers, oscillators and VCOs, oscillator phase noise theory, mixers and frequency dividers for PLLs. A design project is an integral part of the course.

EECS E6321y Advanced digital electronic circuits
4.5 pts. Lect: 3. Professor Seok.
Prerequisite: EECS E4321. Advanced topics in the design of digital integrated circuits. Clocked and non-clocked combinational logic styles. Timing circuits: latches and flip-flops, phase-locked loops, delay-locked loops. SRAM and DRAM memory circuits. Modeling and analysis of on-chip interconnect. Power distribution and power-supply noise. Clocking, timing, and synchronization issues. Circuits for chip-to-chip electrical communication. Advanced technology issues that affect circuit design. The class may include a team circuit design project.

ELEN E6331y Principles of semiconductor physics, I
3 pts. Lect: 2.
Prerequisite: ELEN E4301. Designed for students interested in research in semiconductor materials and devices. Topics include energy bands: nearly free electron and tight-binding approximations, the k.p. method, quantitative calculation of band structures and their applications to quantum structure transistors, photodetectors, and lasers; semiconductor statistics, Boltzmann transport equation, scattering processes, quantum effect in transport phenomena, properties of heterostructures. Quantum mechanical treatment throughout.

ELEN E6332y Principles of semiconductor physics, II
3 pts. Lect: 2.
Prerequisites: ELEN E6331. Optical properties including absorption and emission of radiation, electron-phonon interactions, radiative and phonon-mediated processes, excitons, plasmons, polaritons, carrier recombination and generation, and related optical devices, tunneling phenomena, superconductivity. Quantum mechanical treatment throughout, heavy use of perturbation theory.

ELEN E6333y Semiconductor device physics
3 pts. Lect: 2.
Prerequisites: ELEN E4301 or equivalent. Physics and properties of semiconductors. Transport and recombination of excess carriers. Schottky, P-N, MOS, and heterojunction diodes. Field effect and bipolar junction transistors. Dielectric and optical properties. Optical devices including semiconductor lamps, lasers, and detectors.

ELEN E6412y Lightwave devices
3 pts. Lect: 2.
Prerequisites: ELEN E4411. Electro-optics: principles; electro-optics of liquid crystals and photo-refractive materials. Nonlinear optics: second-order nonlinear optics; third-order nonlinear optics; pulse propagation and solitons. Acousto-optics: interaction of light and sound; acousto-optic devices. Photonic switching and computing: photonic switches; all-optical switches; bistable optical devices. Introduction to fiber-optic communications: components of the fiber-optic link; modulation, multiplexing and coupling; system performance; receiver sensitivity; coherent optical communications.

ELEN E6413y Lightwave systems
3 pts. Lect: 2.
Prerequisites: ELEN E4411. Recommended preparation: ELEN E6412. Fiber optics. Guiding, dispersion, attenuation, and nonlinear properties of fibers. Optical modulation schemes. Photonic components, optical amplifiers. Semiconductor laser transmitters. Receiver design. Fiber optic telecommunication links. Nonregenerative transmission using erbium-doped fiber amplifier chains. Coherent detection. Local area networks. Advanced topics in light wave networks.

ELEN E6414y Photonic integrated circuits
3 pts. Lect: 3.
Photonic integrated circuits are important subsystem components for telecommunications, optically controlled radar, optical signal processing, and photonic local area networks. An introduction to the devices and the design of these circuits. Principle and modelling of dielectic waveguides (including silica on silicon and InP based materials), waveguide devices (simple and star couplers), and surface diffractive elements. Discussion of numerical techniques for modelling circuits, including beam propagation and finite difference codes, and design of other devices: optical isolators, demultiplexers.

ELEN E6430x or y Applied quantum optics
3 pts. Lect: 2.
Prerequisites: Background in electromagnetism (ELEN E3401, E4401, E4411, or PHYS G6092) and quantum mechanics (APPH E3100, E4100, or PHYS G402x). An introduction to fundamental concepts of quantum optics and quantum electrodynamics with an emphasis on applications in nanophotonic devices. The quantization of the electromagnetic field; coherent and squeezed states of light; interaction between light and electrons in the language of quantum electrodynamics (QED); optical resonators and cavity QED; low-threshold lasers; and entangled states of light.

ELEN E6488y Optical interconnects and interconnection networks
3 pts. Lect: 2. Professor Bergman.
Prerequisite: ELEN E4411 or E4488 or an equivalent photonics course. Introduction to optical interconnects and interconnection networks for digital systems. Fundamental optical interconnects technologies, optical interconnection network design, characterization, and performance evaluation. Enabling photonic technologies including free-space structures, hybrid and monolithic integration platforms for photonic on-chip, chip-to-chip, backplane, and node-to-node interconnects, as well as photonic networks on-chip.

EEME E6601x Introduction to control theory
3 pts. Lect: 3. Professor Longman.
Prerequisite: MATH E1210. A graduate-level introduction to classical and modern feedback control that does not presume an undergraduate background in control. Scalar and matrix differential equation models, and solutions in terms of state transition matrices. Transfer functions and transfer function matrices, block diagram manipulations, closed-loop response. Proportional, rate, and integral controllers, and compensators. Design by root locus and frequency response. Controllability, observability. Luenberger observers, pole placement, and linear-quadratic cost controllers.

EEME E6602y Modern control theory
3 pts. Lect: 3.
Prerequisite: EEME E6601 or E4601 or ELEN E6201, or instructor's permission. Singular value decomposition. ARX model and state-space model system identification. Recursive least squares filters and Kalman filters. LQR, H, linear robust control, predictive control. Learning control, repetitive control, adaptive control. Liapunov and Popov stability. Nonlinear adaptive control, nonlinear robust control, sliding mode control.

EEOR E6616x or y Convex optimization
3 pts. Lect: 2.5.
Prerequisites: IEOR E6613 and EEOR E4650. Convex sets and functions, and operations preserving convexity. Convex optimization problems. Convex duality. Applications of convex optimization problems ranging from signal processing and information theory to revenue management. Convex optimization in Banach spaces. Algorithms for solving constrained convex optimization problems.

ELEN E6711x Stochastic models in information systems
4.5 pts. Lect: 3. Professor Baryshnikov.
Prerequisite: IEOR E3658. Foundations: probability review, Poisson processes, discrete-time Markov models, continuous-time Markov models, stationarity, and ergodicity. The course presents a sample-path (time domain) treatment of stochastic models arising in information systems, including at least one of the following areas: communications networks (queueing systems), biological networks (hidden Markov models), Bayesian restoration of images (Gibbs fields), and electric networks (random walks).

ELEN E6712x Communication theory
3 pts. Lect: 3.
Prerequisite: ELEN E4815, or equivalent, or instructor's permission. Representation of bandlimited signals and systems. Coherent and incoherent communications over Gaussian channels. Basic digital modulation schemes. Intersymbol inference channels. Fading multipath channels. Carrier and clock synchronization.

ELEN E6713y Topics in communications
3 pts. Lect: 3.
Prerequisite: ELEN E6712 or E4702 or E4703 or equivalent, or instructor's permission. Advanced topics in communications, such as turbo codes, LDPC codes, multiuser communications, network coding, cross-layer optimization, cognitive radio. Content may vary from year to year to reflect the latest development in the field.

ELEN E6717x Information theory
3 pts. Lect: 2.
Prerequisite: IEOR E3658 or a course in stochastic processes. Corequisite: ELEN E4815. Mutual information and entropy. The source coding theorem. The capacity of discrete memoryless channels and the noisy channel coding theorem. The rate distortion function. Discrete memoryless sources and single-letter distortion measures. Bhattacharya bounds, convolutional codes, and the Viterbi algorithm.

ELEN E6718y Algebraic coding theory
3 pts. Lect: 2.
Prerequisite: IEOR E3658. Elementary concepts of error control codes. Linear block codes. Elements of algebra: Galois fields. Cyclic codes: BCH, Reed Solomon, Goppa codes. Coder, decoder implementation. Decoding algorithms based on spectral techniques. Convolutional codes.

ELEN E6761x Computer communication networks I
3 pts. Lect: 3. Professor Maxemchuk.
Prerequisites: IEOR E3658 and CSEE W4119 or equivalent, or instructor's permission. Focus on architecture protocols and performance evaluation of geographically distributed and local area data networks. Emphasis on layered protocols. Data link layer. Network layer: flow and congestion control routing. Transport layer. Typical Local and Metropolitan Area Network standards: Ethernet, DQDB, FDDI. Introduction to Internetting. Review of relevant aspects of queueing theory to provide the necessary analytical background.

ELEN E6770–6779x or y Topics in telecommunication networks
3 pts. Lect: 2.
Further study of areas such as communication protocols and architectures, flow and congestion control in data networks, performance evaluation in integrated networks. Content varies from year to year, and different topics rotate through the course numbers 6770 to 6779.

ELEN E6820y Speech and audio processing and recognition
4.5 pts. Lect: 3.
Prerequisite: ELEN E4810 or instructor's permission. Fundamentals of digital speech processing and audio signals. Acoustic and perceptual basics of audio. Short-time Fourier analysis. Analysis and filterbank models. Speech and audio coding, compression, and reconstruction. Acoustic feature extraction and classification. Recognition techniques for speech and other sounds, including hidden Markov models.

CSEE E6824y Parallel computer architecture
3 pts. Lect: 2.
Prerequisite: CSEE W4824. Parallel computer principles, machine organization and design of parallel systems including parallelism detection methods, synchronization, data coherence and interconnection networks. Performance analysis and special purpose parallel machines.

CSEE E6847y Distributed embedded systems
3 pts. Lect: 2.
Prerequisite: Any COMS W411X, CSEE W48XX, or ELEN E43XX course, or instructor's permission. An interdisciplinary graduate-level seminar on the design of distributed embedded systems. System robustness in the presence of highly variable communication delays and heterogeneous component behaviors. The study of the enabling technologies (VLSI circuits, communication protocols, embedded processors, RTOSs), models of computation, and design methods. The analysis of modern domain-specific applications including on-chip micro-networks, multiprocessor systems, fault-tolerant architectures, and robust deployment of embedded software. Research challenges such as design complexity, reliability, scalability, safety, and security. The course requires substantial reading, class participation and a research project.

ELEN E6850x Visual information systems
3 pts. Lect: 2.
Prerequisite: ELEN E4830 or instructor's permission. Introduction to critical image technologies in advanced visual information systems, such as content-based image databases, video servers, and desktop video editors. Intended for graduate students. Topics include visual data representation and compression, content-based visual indexing and retrieval, storage system design (data placement, scheduling, and admission control), compressed video editing, and synchronization issues of stored video/audio signals. Programming projects and final presentations are required.

ELEN E6860y Advanced digital signal processing
3 pts. Lect: 2. Professor Nguyen.
Prerequisite: ELEN E4810. This course is designed as an extension to ELEN E4810, with emphasis on emerging techniques in the area of digital signal processing. Topics include multirate signal processing, multidimensional signal processing, short-time Fourier transform, signal expansion in discrete and continuous time, filter banks, multiresolution analysis, wavelets, and their applications to image compression and understanding. Other topics may be included to reflect developments in the field.

CSEE E6861y Computer-aided design of digital systems
3 pts. Lect: 2.
Prerequisites: (i) one semester of advanced digital logic (CSEE W4823 or equivalent, or instructor's permission); and (ii) a basic course in data structures and algorithms (COMS W3133, 3134, 3137, 3139 or 3157, or equivalent, and familiarity with programming. Introduction to modern digital CAD synthesis and optimization techniques. Topics include: modern digital system design (high-level synthesis, register-transfer level modeling, algorithmic state machines, optimal scheduling algorithms, resource allocation and binding, retiming), controller synthesis and optimization, exact and heuristic two-level logic minimization, advanced multi-level logic optimization, optimal technology mapping to library cells (for delay, power and area minimization), advanced data structures (binary decision diagrams), SAT solvers and their applications, static timing analysis, and introduction to testability. Includes hands-on small design projects using and creating CAD tools.

CSEE E6868x or y System-on-chip platforms
3 pts. Lect: 3.
Prerequisites: COMS W3157 and CSEE W3827. Design and programming of system-on-chip (SoC) platforms. Topics include: overview of technology and economic trends, methodologies and supporting CAD tools for system-level design and verification, software simulation and virtual platforms, models of computation, the SystemC language, transaction-level modeling, hardware-software partitioning, high-level synthesis, memory organization, device drivers, on-chip communication architectures, power management and optimization, integration of programmable cores and specialized accelerators. Case studies of modern SoC platforms for various classes of applications.

EECS E6870x or y Speech recognition
3 pts. Lect: 2.
Prerequisites: Basic probability and statistics. Theory and practice of contemporary automatic speech recognition. Gaussian mixture distributions, hidden Markov models, pronunciation modeling, decision trees, finite-state transducers, and language modeling. Selected advanced topics will be covered in more depth.

ELEN E6873x or y Detection and estimation theory
3 pts. Lect: 2.
Prerequisite: ELEN E4815. Introduction to the fundamental principles of statistical signal processing related to detection and estimation.

Hypothesis testing, signal detection, parameter estimation, signal estimation, and selected advanced topics. Suitable for students doing research in communications, control, signal processing, and related areas.

ELEN E6880-6889x or y Topics in signal processing
3 pts. Lect: 2.
Prerequisite: ELEN E4810. Advanced topics in signal processing, such as multidimensional signal processing, image feature extraction, image/video editing and indexing, advanced digital filter design, multirate signal processing, adaptive signal processing, and wave-form coding of signals. Content varies from year to year, and different topics rotate through the course numbers 6880 to 6889.

EECS E6890-6899x or y Topics in information processing
3 pts. Lect: 2.
Advanced topics spanning electrical engineering and computer science such as speech processing and recognition, image and multimedia content analysis, and other areas drawing on signal processing, information theory, machine learning, pattern recognition, and related topics. Content varies from year to year, and different topics rotate through the course numbers 6890 to 6899.

ELEN E6900–6909x or y Topics in electrical and computer engineering
3 pts. Lect: 2.
Prerequisite: Instructor's permission. Selected topics in electrical and computer engineering. Content varies from year to year, and different topics rotate through the course numbers 6900 to 6909.

ELEN E6945x or y Device nanofabrication
3 pts. Lect: 3.
Prerequisites: ELEN E3106 and E3401, or equivalents. Recommended: ELEN E4944. This course provides an understanding of the methods used for structuring matter on the nanometer length: thin-film technology; lithographic patterning and technologies including photon, electron, ion and atom, scanning probe, soft lithography, and nanoimprinting; pattern transfer; self-assembly; process integration; and applications.

ELEN E6950x Wireless and mobile networking, I
4.5 pts. Lect: 2. Lab: 1. Professor Jelenkovic.
Corequisite: ELEN E6761 or instructor's permission. Overview of mobile and wireless networking. Fundamental concepts in mobile wireless systems: propagation and fading, cellular systems, channel assignment, power control, handoff. Examples of second-generation circuits-switched systems and standards. Quantitative homework assignments may require use of a mathematical software package.

ELEN E6951y Wireless and mobile networking, II
3 pts. Lect: 2. Lab: 1. Professor Zussman.
Prerequisite: CSEE W4119, ELEN E6761, or instructor's permission. Third-generation packet switched systems, wireless LANs, mobile computing and communications. Study of some current research topics. Quantitative homework assignments may require use of a mathematical software package. A project based on readings from the literature will be required.

ELEN E6999 Curricular practical training
1–3 pts.
Prerequisites: Obtained internship and approval from a faculty adviser. Only for Electrical Engineering and Computer Engineering graduate students who include relevant off-campus work experience as part of their approved program of study. Final report required. May not be taken for pass/fail credit or audited.

EEME E8601y Advanced topics in control theory
3 pts. Lect: 3.
See entry under "Courses in Mechanical Engineering" for description.

ELEN E9001x and y–E9002 Research
0–6 pts.
Prerequisite: Requires approval by a faculty member who agrees to supervise the work. Points of credit to be approved by the department. Requires submission of an outline of the proposed research for approval by the faculty member who is to supervise the work of the student. The research facilities of the department are available to qualified students interested in advanced study.

ELEN E9011x and y–E9012 Doctoral research
0–6 pts.
Prerequisite: Requires approval by a faculty member who agrees to supervise the work. Points of credit to be approved by the department. Open only to doctoral students who have passed the qualifying examinations. Requires submission of an outline of the proposed research for the approval of the faculty member who is to supervise the work of the student.

ELEN E9800x and y Doctoral research instruction
3, 6, 9 or 12 pts.
A candidate for the Eng.Sc.D. degree in electrical engineering must register for 12 points of doctoral research instruction. Registration in ELEN E9800 may not be used to satisfy the minimum residence requirement for the degree.

ELEN E9900x and y–9900 Doctoral dissertation
0 pts.
A candidate for the doctorate may be required to register for this course every term after the student's course work has been completed, and until the dissertation has been accepted.

COURSES IN ELECTRICAL ENGINEERING OFFERED OCCASIONALLY

EEHS E3900y History of telecommunications: from the telegraph to the Internet
3 pts. Lect: 3.
Historical development of telecommunications from the telegraphy of the mid-1800s to the Internet at present. Included are the technologies of telephony, radio, and computer communications. The coverage includes both the technologies themselves and the historical events that shaped, and in turn were shaped by, the technologies. The historical development, both the general context and the particular events concerning communications, is presented chronologically. The social needs that elicited new technologies and the consequences of their adoption are examined. Throughout the course, relevant scientific and engineering principles are explained as needed. These include, among others, the concept and effective use of spectrum, multiplexing to improve capacity, digital coding, and networking principles. There are no prerequisites, and no prior scientific or engineering knowledge is required. Engineering students may not count this course as a technical elective. The course shares lectures with EEHS E4900, but the work requirements differ somewhat.

ELEN E3999x or y Electrical engineering design challenge
1 pt.
Prerequisite: Approval by a faculty member who agrees to supervise the work. May be repeated for credit, but no more than 3 total points may be used for degree credit. Short-term design project organized as a faculty-led team competition. Particular design targets are set that vary by semester. A set of hardware and software constraints is specified. The project takes place over an advertised subset of the semester, beginning around the third week.

ELEN E4215y Analog filter synthesis and design
3 pts. Lect: 3.
Prerequisites: ELEN E3201 and ELEN E3801, or equivalent. Approximation techniques for magnitude, phase, and delay specifications , transfer function realization sensitivity, passive LC filters, active RC filters, MOSFET-C filters, Gm-C filters, switched-capacitor filters, automatic tuning techniques for integrated filters. Filter noise. A design project is an integral part of the course.

ELEN E4302x or y Magnetic sensors and instruments for medical imaging
3 pts. Lect: 2.5, Lab: 0.5.
Prerequisite: ELEN E3106, ELEN E3401, or instructor's permission. Physics of nuclear magnetic resonance (NMR) and superconducting quantum interference device (SQUID). Design

and operation of superconducting DC magnet, RF receiver, Josephson junction, and integrated SQUID. Principles of biomedical sensoring systems including Magnetic Resonance Imaging (MRI), SQUID magnetometer, and NMR spectroscopy. Medical image formation and processing.

ELEN E4350y VLSI design laboratory
3 pts. Lab: 3.
Prerequisites: ELEN E4321 and E4312, or instructor's permission. Design of a CMOS mixed-signal integrated circuit. The class divides up into teams to work on mixed-signal integrated circuit designs. The chips are fabricated to be tested the following term. Lectures cover use of computer-aided design tools, design issues specific to the projects, and chip integration issues. This course shares lectures with E6350, but the complexity requirements of integrated circuits are lower.

ELEN E4405x Classical nonlinear optics
3 pts. Lect: 3.
Prerequisite: ELEN E4401. Waves in anisotropic media. Maxwell's equations and constitutive relations. Fresnel equations. Optical waves in anisotropic crystals. Birefringence. Waves in nonlinear media. Plasma model. Electro-optic, Pockels, and Kerr effects. Second harmonic generation and phase matching. Parametric amplification. Backward-wave oscillator. Acousto-optic beam deflection and light modulation.

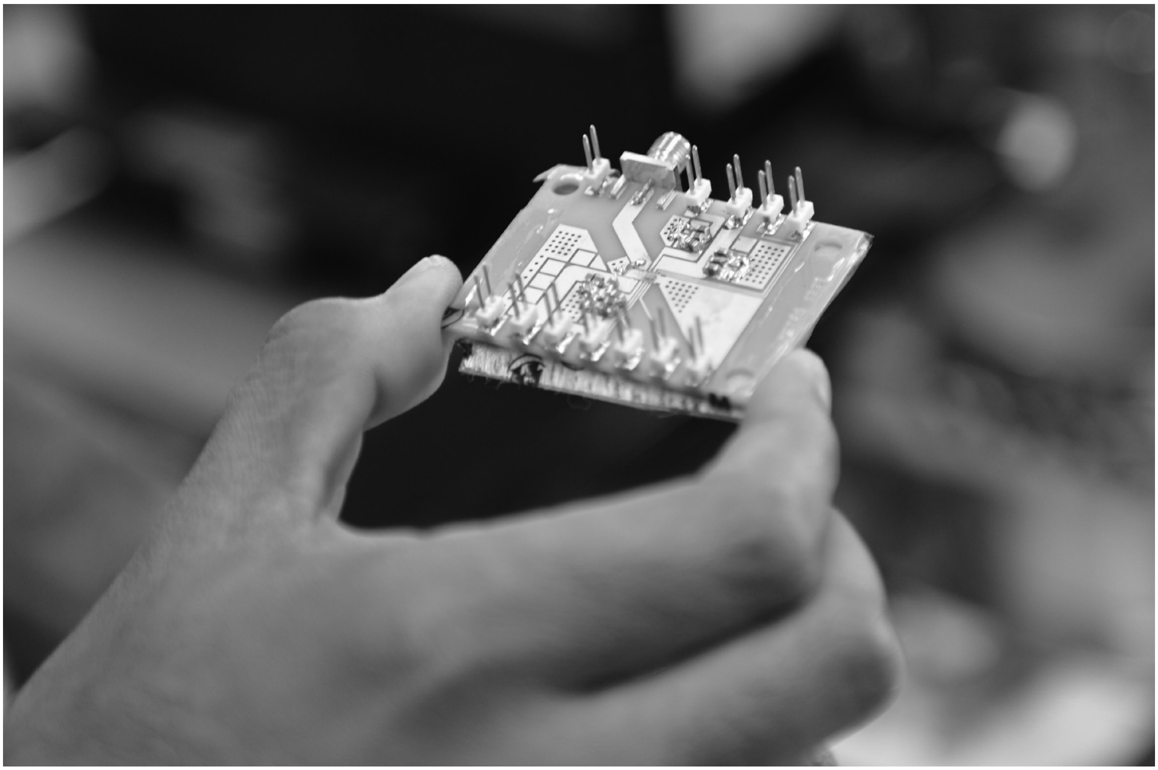
ELEN E4420x Topics in electromagnetics
3 pts. Lect: 3.
Prerequisites: Undergraduate electromagnetic theory. Selected topics in the theory and practice of electromagnetics, varying from year to year. Topic for current term will be available in the department office one month before registration. This course may be taken more than once when topics are different. Possible topics: microwave theory and design (generalized waveguides, excitation and coupling of waveguides, junctions, microwave networks, periodic structures, optical fibers); antennas (filamentary antennas, arrays, aperture radiation, system properties, pattern synthesis); electrodynamics (special relativity, radiation by charged particles, relativistic beams, free electron lasers).

ELEN E4741x Introduction to biological sensory systems
3 pts. Lect: 3.
Corequisite: IEOR E3658. Introduction to vision and hearing using engineering principles. Nature of sound and light; minimum detectable energy for human observers; excitation of the visual and hearing systems; rods, cones, and hair-cell receptors; the experiment of Hecht, Shlaer, and Pirenne; Poisson counting statistics; stimulus-based modeling; detection and false-alarm probabilities; de Vries-Rose square-root law; Weber's law; relation of sensory and communication systems.

CSEE W4825y Digital systems design
3 pts. Lect: 3.
Prerequisite: CSEE W3827. Dynamic logic, field programmable gate arrays, logic design languages, multipliers. Special techniques for multilevel NAND and NOR gate circuits. Clocking schemes for one- and two-phase systems. Fault checking: scan method, built-in-test. Survey of logic simulation methods. Other topics to be added as appropriate.

ELEN E6140x Gallium arsenide materials processing
3 pts. Lect: 3.
Prerequisite: ELEN E4301 or instructor's permission. Materials and device aspects of GaAs and compound technologies, electronic properties of GaAs, growth techniques (bulk and epitaxial), surface and etching properties, implantation, MESFETS, transferred electron devices, Impatt diodes, HEMTS, HBTs.

ELEN E6151y Surface physics and analysis of electronic materials
3 pts. Lect: 2.
Prerequisite: Instructor's permission. Basic physical principles of methods of surface analysis, surfaces of electronic materials including structure and optical properties (auger electron spectroscopy, X-ray photoemission, ultraviolet photoelectron spectroscopy, electron energy loss spectroscopy, inverse photoemission, photo stimulated desorption,



and low energy electron diffraction), physical principles of each approach.

ELEN E6211x or y Circuit theory
3 pts. Lect: 3.
Prerequisites: ELEN E3331 and ELEN E3801. An axiomatic development of circuit theory. Circuit theorems, circuit topology, general methods of circuit analysis. Normal form characterizations. Scattering characterization and sensitivity function. Basic network synthesis methods: immittance and transfer function realization, multiport realization, approximation techniques.

ELEN E6261y Computational methods of circuit analysis
3 pts. Lect: 3.
Prerequisites: ELEN E3331 and APMA E3101. Computational algorithms for DC, transient, and frequency analysis of linear and nonlinear circuits. Formulation of equations: state equations, hybrid equations, sparse tableaux. Solution techniques: iterative methods to solve nonlinear algebraic equations; piecewise linear methods; sparse matrix techniques; numerical integration of stiff, nonlinear differential equations, companion network models; waveform relaxation.

ELEN E6302x or y MOS transistors
3 pts. Lect: 2.
Prerequisite: ELEN E3106 or equivalent. Operation and modelling of MOS transistors. MOS two- and three-terminal structures. The MOS transistor as a four-terminal device; general charge-sheet modelling; strong, moderate, and weak inversion models; short-and-narrow-channel effects; ion-implanted devices; scaling considerations in VLSI; charge modelling; large-signal transient and small-signal modelling for quasistatic and nonquasistatic operation.

ELEN E6304x or y Topics in electronic circuits
3 pts. Lect: 3.
Prerequisite: Instructor's permission. State-of-the-art techniques in integrated circuits. Topics may change from year to year.

ELEN E6350y VLSI design laboratory
3 pts. Lab: 3.
Prerequisites: ELEN E4321 and E4312, or instructor's permission. Design of a CMOS mixed-signal integrated circuit. The class divides up into teams to work on mixed-signal integrated circuit designs. The chips are fabricated to be tested the following term. Lectures cover use of computer-aided design tools, design issues specific to the projects, and chip integration issues. This course shares lectures with E4350 but the complexity requirements of integrated circuits are higher.

ELEN E6403y Classical electromagnetic theory
4.5 pts. Lect: 3.
Prerequisite: One term of undergraduate electromagnetic theory. A mathematical physics approach to electromagnetic phenomena. Poisson, Laplace equations; Green's functions. Theorems of electrostatics. Multipole expansions. Energy relations and stress tensor. Maxwell's equations in stationary and moving media. The wave equation, energy and momentum theorems, potentials, choice of gauge.

EEME E6610x Optimal control theory
3 pts. Lect: 3.
Prerequisite: ELEN E6201 or EEME E6601. Objectives of optimal control. Continuous and discrete control problems. Calculus of variations: Mayer and Bolza; Pontryagin's maximum principle. Bang-bang and singular controls. Existence of optimal control. Hamilton-Jacobi theory and dynamic programming. Numerical methods. Optimal feedback control regulatory problems. Linear-quadratic-Gaussian estimation. Applications.

EEME E6612x or y Control of nonlinear dynamic systems
3 pts. Lect: 3.
Prerequisites: EEME E6601 or ELEN E6201 and an undergraduate controls course. Fundamental properties of nonlinear systems; qualitative analysis of nonlinear systems; nonlinear controllability and observability; nonlinear stability; zero dynamics and inverse systems; feedback stabilization and linearization; sliding control theory; nonlinear observers; describing functions.

ELEN E6731y Satellite communication systems
3 pts. Lect: 2. Not offered in 2011–2012.
Prerequisite: ELEN E4702. Introduction to satellite communication, with emphasis on characterization and systems engineering of the transmission channel. Power budgets, antennas, transponders, multiple access, and frequency re-use techniques. Noise, intermodulation, interference, and propagation effects. Modulation methods, earth terminals, and standards. Digital transmission and advanced systems.

ELEN E6762y Computer communication networks, II
3 pts. Lect: 2.
Prerequisite: ELEN E6761. Broadband ISDN, services and protocols; ATM. Traffic characterization and modeling: Markov-modulated Poisson and Fluid Flow processes; application to voice, video, and images. Traffic Management in ATM networks: admission and access control, flow control. ATM switch architectures; input/output queueing. Quality of service (QoS) concepts.

ELEN E6763y Digital circuit switched networks
3 pts. Lect: 2.
Prerequisite: ELEN E6761 or instructor's permission. Current topics in digital circuit switching: introduction to circuit switching, comparison with packet switching, elements of telephone traffic engineering, space and time switching, call processing in digital circuit-switched systems, overload control mechanisms, nonhierarchical routing, common channel signaling, introduction to integrated services digital networks. Examples of current systems are introduced throughout. Emphasis on modeling and quantitative performance analysis. Queueing models introduced where possible.

ELEN E6781y Topics in modeling and analysis of random phenomena
3 pts. Lect: 3.
Prerequisite: ELEN E6711. Recommended preparation: a course on real analysis and advanced probability theory. Current methodology in research in stochastic processes applied to communication, control, and signal processing. Topics vary from year to year to reflect student interest and current developments in the field.

CSEE E6831y Sequential logic circuits
3 pts. Lect: 3.
Prerequisite: CSEE W3827 or any introduction to logic circuits. Generation and manipulation of flow table descriptions to asynchronous sequential functions. Coding of flow tables to satisfy various design criteria. Delays, races, hazards, metastability. Analysis of latches to determine key parameters. Bounds of input rates. Clocking schemes for synchronous systems. Synthesis of self-timed systems using 4-phase or 2-phase handshakes.

CSEE E6832x or y Topics in logic design theory
3 pts. Lect: 3.
Prerequisite: CSEE W3827 or any introduction to logic circuits. A list of topics for each offering of the course is available in the department office one month before registration. May be taken more than once if topics are different. Iterative logic circuits applied to pattern recognition. Finite state machines; alternative representations, information loss, linear circuits, structure theory. Reliability and testability of digital systems.

ELEN E6920x or y Topics in VLSI systems design
3 pts. Lect: 2.
Prerequisite: ELEN E4321. Design automation: layout, placement, and routing. Circuit simulation algorithms and optimization of performance and area. Multiprocessor computing systems. Verification of testing. Topics may change from year to year.

ELEN E8701y Point processes in information and dynamical systems
3 pts. Lect: 3.
Prerequisite: ELEN E6711 or equivalent. Recommended preparation: Course in measure theory or advanced probability theory. Probability and point processes. Random intensity rate, martingales, and the integral representation of point process martingales. Recursive estimation, the theory of innovations, state estimate for queues. Markovian queueing networks. Hypothesis testing, the separation between filtering and detection. Mutual information and capacity for the Poisson-type channel. Stochastic control, dynamic programming for intensity control.

ELEN E9060x or y Seminar in systems biology
3 pts. Lect: 2.
Open to doctoral candidates, and to qualified M.S. candidates with instructor's permission. Study of recent developments in the field of systems biology.

EEBM E9070x or y Seminar in computational neuroscience and neuroengineering
3 pts. Lect: 2.
Open to doctoral candidates and qualified M.S. candidates with instructor's permission. Study of recent developments in computational neuroscience and neuroengineering.

ELEN E9101x or y Seminar in physical electronics
3 pts. Lect: 2.
Prerequisites: Quantum electronics and ELEN E4944, or instructor's permission. Advanced topics in classical and quantum phenomena that are based on ion and electron beams, gas discharges, and related excitation sources. Application to new laser sources and microelectronic fabrication.

ELEN E9201x or y Seminar in circuit theory
3 pts. Lect: 2.
Open to doctoral candidates, and to qualified M.S. candidates with instructor's permission. Study of recent developments in linear, nonlinear, and distributed circuit theory and analysis techniques important to the design of very large scale integrated circuits.

ELEN E9301x or y Seminar in electronic devices
3 pts. Lect: 2.
Open to doctoral candidates, and to qualified M.S. candidates with instructor's permission. Theoretical and experimental studies of semiconductor physics, devices, and technology.

ELEN E9303x or y Seminar in electronic circuits
3 pts. Lect: 2.
Open to doctoral candidates, and to qualified M.S. candidates with instructor's permission. Study of recent developments in electronic circuits.

ELEN E9402x or y Seminar in quantum electronics
3 pts. Lect: 2.
Open to doctoral candidates, and to qualified M.S. candidates with instructor's permission. Recent experimental and theoretical developments in various areas of quantum electronics research. Examples of topics that may be treated include novel nonlinear optics, lasers, transient phenomena, and detectors.

ELEN E9403x or y Seminar in photonics
3 pts. Lect: 2.
Prerequisite: ELEN E4411. Open to doctoral candidates, and to qualified M.S. candidates with instructor's permission. Recent experimental and theoretical developments in various areas of photonics research. Examples of topics that may be treated include squeezed-light generation, quantum optics, photon detection, nonlinear optical effects, and ultrafast optics.

ELEN E9404x or y Seminar in lightwave communications
3 pts. Lect: 2.
Open to doctoral candidates, and to qualified M.S. candidates with instructor's approval. Recent theoretical and experimental developments in light wave communications research. Examples of topics that may be treated include information capacity of light wave channels, photonic switching, novel light wave network architectures, and optical neural networks.

ELEN E9501x or y Seminar in electrical power networks
3 pts. Lect: 2.
Prerequisites: Open to doctoral candidates, and to qualified M.S. candidates with the instructor's permission. Recent developments in control & optimization for power systems, design of smart grid, and related topics.

ELEN E9701x or y Seminar in information and communication theories
3 pts. Lect: 2.
Open to doctoral candidates, and to qualified M.S. candidates with instructor's permission. Recent developments in telecommunication networks, information and communication theories, and related topics.

ELEN E9801x or y Seminar in signal processing
3 pts. Lect: 2.
Open to doctoral candidates, and to qualifies M.S. candidates with instructor's approval. Recent developments in theory and applications of signal processing, machine learning, content analysis, and related topics.