Electrical & Systems Engineering

About Electrical & Systems Engineering

The mission of our undergraduate programs is to instill in students the knowledge and perspective, appropriate both for a professional career and for the pursuit of advanced degrees, in fields that rely on key electrical engineering and systems principles and practices. Such principles and practices include rigorous quantitative reasoning and robust engineering design. This mission is accomplished by ensuring that students achieve both depth and breadth of knowledge in their studies and by maintaining a high degree of flexibility in the curriculum. Our programs also seek to provide good preparation for life, including the ability to communicate in written and oral forms and a desire to continue learning throughout life. In addition, they aim to provide the opportunity and training for students to acquire the skills and attitudes to become leaders.

The department offers courses of study leading to degrees in both electrical engineering and systems science and engineering. Opportunities for study and research currently available in the department include semiconductor theory and devices, optoelectronics, nanophotonics, communication theory and systems, information theory, signal and image processing, tomographic imaging, linear and nonlinear dynamics and control, robotics, identification and estimation, multisensor fusion and navigation, computational mathematics, optimization, optimal control, autonomous systems, operations research, and financial engineering. Students are encouraged to participate in research activities as soon as they have received training in the fundamentals appropriate for a given research area.

Electrical engineering is the profession for those intrigued with electrical phenomena and eager to contribute their skills to a society increasingly dependent on electricity and sophisticated electronic devices. It is a profession of broad scope with many specialty careers designed for engineers who seek an endless diversity of career paths on the cutting edge of technology. The Institute of Electrical and Electronics Engineers publishes transactions on about 60 different topics, from aerospace and electronic systems to visualization and computer graphics. This is a breadth so great that no single electrical engineering department can hope to span it. Moreover, those fields themselves encompass still more fascinating specialties. We give the basics; the future is yours to shape.

Systems science and engineering is based on an approach that views an entire system of components as an entity rather than simply as an assembly of individual parts; each component is designed to fit properly with the other components rather than to function by itself. The engineering and mathematics of systems is a rapidly developing field. It is one of the most modern segments of applied mathematics, as well as an engineering discipline. It is concerned with the identification, modeling, analysis, design and control of systems that are potentially as large and complex as the U.S. economy or as precise and vital as a space voyage. Its interests run from fundamental theoretical questions to the implementation of operational systems. It draws on the most modern and advanced areas of mathematics. A very important characteristic of the systems field is that its practitioners must, of necessity, interact within a wide interdisciplinary environment, not only with various engineers and scientists but also with economists, biologists or sociologists. Such interaction is both emphasized and practiced in the programs.

Our Department of Electrical & Systems Engineering offers a challenging basic curriculum, a broadly qualified faculty, and modern facilities so that students can receive a contemporary preparation for a career in electrical or systems engineering.

Undergraduate Degree Programs

The Department of Electrical & Systems Engineering (ESE) offers four undergraduate degree programs: two professional degrees and two applied science degrees. The two professional degrees are the Bachelor of Science in Electrical Engineering (BSEE) and the Bachelor of Science in Systems Science & Engineering (BSSSE). These two programs are accredited by the Engineering Accreditation Commission of ABET (http://www.abet.org). The two applied science degrees are the Bachelor of Science in Applied Science (Electrical Engineering) and the Bachelor of Science in Applied Science (Systems Science & Engineering). All programs have flexible curricula as well as specific requirements, and students may elect programs of study tailored to individual interests and professional goals.

In the professional BSEE curriculum, there are required courses in electrical circuits, signals and systems, digital systems and electromagnetic fields, along with laboratory and design courses, which provide students with a common core of experience. Subsequently, one may orient the program toward breadth, so that many disciplines within the profession are spanned or toward a specialty with more emphasis on depth in one or more disciplines. Areas of specialization include modern electronics, applied physics, telecommunications, control systems, and signal and image processing.

Students in the professional BSSSE degree program take required courses in engineering mathematics, signals and systems, operations research, and automatic control systems, along with laboratory and design courses. This program emphasizes the importance of real-world applications of systems theory, and accordingly students are required to take a concentration of courses in one of the traditional areas of engineering or science. There are numerous elective courses in control theory and systems, signal processing, optimization,
Students enrolled in any of the ESE undergraduate degree programs have a variety of opportunities to augment their educational experience at Washington University. Students may participate in the Pre-Medical Engineering program or in the Cooperative Education program. Some students pursue double majors, in which two sets of degree requirements, either within or outside the ESE department, are satisfied concurrently.

Students who seek a broad undergraduate education in electrical engineering or systems science and engineering but plan on careers outside of engineering may pursue the applied science degrees: Bachelor of Science in Applied Science (Electrical Engineering) and Bachelor of Science in Applied Science (Systems Science & Engineering). These programs of study are appropriate for students planning to enter medical, law or business school, who desire a more technical undergraduate experience than what otherwise may be available to them.

The ESE department also offers a variety of educational opportunities for students enrolled in other departments. These include the second major in systems science and the second major in electrical engineering science, which are open to students inside as well as outside of the School of Engineering & Applied Science, such as the College of Arts & Sciences and the School of Business. They also include the minor in applied physics & electrical engineering, the minor in electrical engineering, the minor in energy engineering, the minor in mechatronics, the minor in robotics, and the minor in systems science & engineering.

**BS–Master’s Programs in Electrical & Systems Engineering**

Students enrolled in any of the undergraduate degree programs in the School of Engineering & Applied Science may choose to extend their educational experience by enrolling in a five-year BS–Master’s program. The Master of Science in Electrical Engineering (MSEE), Master of Science in Systems Science and Mathematics (MSSSM), Master of Control Engineering (MCE), Master of Engineering in Robotics (MER), and Master of Science in Engineering Data Analytics and Statistics (MSDAS) degrees are participating graduate degrees, and these may be combined with any undergraduate degree that provides the appropriate background.

General requirements for the BS–Master’s programs include the residency and other applicable requirements of the university and the School of Engineering & Applied Science, which are found elsewhere in this catalog. In summary, students must complete all the degree requirements for both the undergraduate and graduate degrees (at least 120 units plus 30 units; 150 units) but are not required to complete all the undergraduate degree requirements first.

**Faculty**

**Chair**

R. Martin Arthur
Newton R. and Sarah Louisa Glasgow Wilson Professor of Engineering
PhD, University of Pennsylvania
Ultrasonic imaging, electrocardiography

**Endowed Professors**

Arye Nehorai
Eugene and Martha Lohman Professor of Electrical Engineering
PhD, Stanford University
Statistical signal processing, machine learning, imaging, biomedicine

Joseph A. O’Sullivan
Samuel C. Sachs Professor of Electrical Engineering
Dean, UMSL/WashU Joint Undergraduate Engineering Program
PhD, Notre Dame University
Information theory, statistical signal processing, imaging science with applications in medicine and security, and recognition theory and systems

Lan Yang
Edward H. & Florence G. Skinner Professor of Engineering
PhD, California Institute of Technology
Nano/micro photonics, ultra high-quality optical microcavities, ultra-low-threshold microlasers, nano/micro fabrication, optical sensing, single nanoparticle detection, photonic molecules, photonic materials

**Professors**

Shantanu Chakrabartty
PhD, Johns Hopkins University
New frontiers in unconventional analog computing techniques using silicon and hybrid substrates, fundamental limits of energy efficiency, sensing and resolution by exploiting computational and adaptation primitives inherent in the physics of devices

Hiroaki Mukai
Professor
PhD, University of California, Berkeley
Theory and computational methods for optimization, optimal control, systems theory, electric power system operations, differential games

Phone: 314-935-5565
Website: http://ese.wustl.edu
Heinz Schaettler
PhD, Rutgers University
Optimal control, nonlinear systems, mathematical models in biomedicine

**Associate Professors**

- **Jr-Shin Li**
  - Das Family Distinguished Career Development Associate Professor
  - PhD, Harvard University
  - Mathematical control theory, optimization, quantum control, biomedical applications

- **Robert E. Morley Jr.**
  - DSc, Washington University
  - Computer and communication systems, VLSI design, digital signal processing

**Assistant Professors**

- **ShiNung Ching**
  - Das Family Distinguished Career Development Assistant Professor
  - PhD, University of Michigan
  - Systems and control in neural medicine, nonlinear and constrained control, physiologic network dynamics, stochastic control

- **Zachary Feinstein**
  - PhD, Princeton University
  - Financial engineering, operations research, variational analysis

- **Ulugbek Kamilov**
  - PhD, École Polytechnique Fédérale de Lausanne, Switzerland
  - Computational imaging, signal processing, biomedical imaging

- **Matthew D. Lew**
  - PhD, Stanford University
  - Microscopy, biophotonics, computational imaging, nano-optics

- **Jung-Tsung Shen**
  - Das Family Distinguished Career Development Assistant Professor
  - PhD, Massachusetts Institute of Technology
  - Theoretical and numerical investigations on nanophotonics, optoelectronics, plasmonics, metamaterials

**Senior Professors**

- **I. Norman Katz**
  - PhD, Massachusetts Institute of Technology
  - Numerical analysis, differential equations, finite element methods, locational equilibrium problems, algorithms for parallel computations

- **Paul S. Min**
  - PhD, University of Michigan
  - Routing and control of telecommunication networks, fault tolerance and reliability, software systems, network management

- **William F. Pickard**
  - PhD, Harvard University
  - Biological transport, electrobiology, energy engineering

- **Daniel L. Rode**
  - PhD, Case Western Reserve University
  - Optoelectronics and fiber optics, semiconductor materials, light-emitting diodes (LEDs) and lasers, semiconductor processing, electronics

- **Ervin Y. Rodin**
  - PhD, University of Texas at Austin
  - Optimization, differential games, artificial intelligence, mathematical modeling

- **Barbara A. Shrauner**
  - PhD, Harvard University (Radcliffe)
  - Plasma processing, semiconductor transport, symmetries of nonlinear differential equations

- **Donald L. Snyder**
  - PhD, Massachusetts Institute of Technology
  - Communication theory, random process theory, signal processing, biomedical engineering, image processing, radar

**Chuan Wang**
- PhD, University of Southern California
- Flexible electronics, stretchable electronics, printed electronics, nanomaterials, optoelectronics

**Shen Zeng**
- PhD, University of Stuttgart
- Systems and control theory, data-based analysis and control of complex dynamical systems, inverse problems, biomedical applications

**Xuan "Silvia" Zhang**
- PhD, Cornell University
- Robotics, cyber-physical systems, hardware security, ubiquitous computing, embedded systems, computer architecture, VLSI, electronic design automation, control optimization, and biomedical devices and instrumentation
Barry E. Spielman  
PhD, Syracuse University  
High-frequency/high-speed devices, RF & MW integrated circuits, computational electromagnetics

Tzyh Jong Tarn  
DSc, Washington University  
Quantum mechanical systems, bilinear and nonlinear systems, robotics and automation, life science automation

Professors of Practice

Dedric Carter  
PhD, Nova Southeastern University  
MBA, MIT Sloan School of Management

Dennis Mell  
MS, University of Missouri-Rolla

Ed Richter  
MS, Washington University

Jason Trobaugh  
DSc, Washington University

Senior Lecturer

Martha Hasting  
PhD, Saint Louis University

Lecturers

Randall Brown  
PhD, Washington University

James Feher  
PhD, Missouri University of Science and Technology

Randall Hoven  
MS, Johns Hopkins University

Vladimir Kurenok  
PhD, Belarus State University (Minsk, Belarus)

Tsitsi Madziwa-Nussinov  
PhD, University of California, Los Angeles

Jinsong Zhang  
PhD, University of Miami

Professors Emeriti

Lloyd R. Brown  
DSc, Washington University  
Automatic control, electronic instrumentation

David L. Elliott  
PhD, University of California, Los Angeles  
Mathematical theory of systems, nonlinear difference, differential equations

Majors

Please visit the following pages for information about the

• BS in Electrical Engineering (http://bulletin.wustl.edu/undergrad/engineering/electrical/bs-electrical)
• BS in Systems Science & Engineering (http://bulletin.wustl.edu/undergrad/engineering/electrical/bs-systems)
• BS in Applied Science (Electrical Engineering) (http://bulletin.wustl.edu/undergrad/engineering/electrical/bs-applied-electrical)
• BS in Applied Science (Systems Science & Engineering) (http://bulletin.wustl.edu/undergrad/engineering/electrical/bs-applied-systems)
• Second Major in Electrical Engineering Science (http://bulletin.wustl.edu/undergrad/engineering/electrical/second-major-electrical)
• Second Major in Systems Science (http://bulletin.wustl.edu/undergrad/engineering/electrical/second-major-systems)
• Second Major in Financial Engineering (http://bulletin.wustl.edu/undergrad/engineering/electrical/second-major-financial)

Minors

Please visit the following pages for information about the minors in

• Applied Physics & Electrical Engineering (http://bulletin.wustl.edu/undergrad/engineering/electrical/bs-applied-physics-electrical)
• Electrical Engineering (http://bulletin.wustl.edu/undergrad/engineering/electrical/bs-electrical)
• Energy Engineering (ESE) (http://bulletin.wustl.edu/undergrad/engineering/electrical/bs-energy)
• Mechatronics (ESE) (http://bulletin.wustl.edu/undergrad/engineering/electrical/bs-mechatronics)
• Robotics (http://bulletin.wustl.edu/undergrad/engineering/electrical/bs-robotics)
• Systems Science & Engineering (http://bulletin.wustl.edu/undergrad/engineering/electrical/bs-systems)

Courses


E35 ESE 101 Introduction to Engineering Tools: MATLAB and Simulink

MATLAB and Simulink are important tools in quickly analyzing different designs in many engineering disciplines and are also perhaps the most used software in many engineering schools. Gain skills in the basics of the array-based language MATLAB to write programs, including scripts and functions, to calculate and display variables and images. Learn the basics of Simulink to build and simulate models from standard blocks. Discover both MATLAB and Simulink in an environment with supervised practice and hands-on experience. Practice problems are
chosen from different engineering fields as well as from a few socio-economic fields so that students can see the software being exploited in real life applications. This is a pass/fail course. Prerequisite: freshman standing. Credit 1 unit. EN: TU

E35 ESE 103 Introduction to Electrical Engineering
A hands-on introduction to electrical engineering to put the fun into the electrical engineering fundamentals. Experiments are designed to be easy to conduct and understand. Some of the technologies explored are used in a variety of applications including ultrasound imaging, computed tomography, DC motors, analog to digital converters and credit card readers. Students work in groups of two in the newly renovated Urbauer 115 laboratory. Each station is equipped with modern electronic test equipment and a computer with an integrated Data Acquisition system. Using this lab equipment, students design and build solutions to the exercises. The students also learn to program in LabVIEW to control the Data Acquisition system and process the acquired signals. Also, throughout the semester, presentations are given by the ESE faculty about their research. Credit 1 unit. EN: TU

E35 ESE 105 Introduction to Electrical and Systems Engineering
This course will offer students a rigorous introduction to fundamental mathematical underpinnings of ESE and their relationship to a number of contemporary application areas. Major emphasis will be placed on linear algebra and associated numerical methods, including the use of MATLAB. Topics covered will include vector spaces, linear transformations, matrix manipulations and eigenvalue decomposition. Students will learn how this mathematical theory is enacted in ESE through the completion of four case studies spanning application areas: (i) Dynamical Systems and Control, (ii) Imaging, (iii) Signal Processing, and (iv) Circuits. Credit 3 units. EN: TU

E35 ESE 141 Introductory Robotics
A hands-on introduction to robotics. Project-oriented course where students build and program a robot guided by upper-division students. Friendly competition at the end of semester. Students gain electrical lab experience, programming experience, and a guided introduction into the field of robotics. Recommended to freshmen and sophomores. This is a pass/fail course. Credit 1 unit. EN: TU

E35 ESE 151 Introduction to Systems Science and Engineering
Systems Science and Engineering (SSE) has grown in applicability to many industries. This course will provide an overview of the broad applicability of the analytical methods studied in SSE, as well as introduce many of these analytical methods. Each module of the course will present a domain area (e.g., energy, health care, etc.) with examples of how one of the SSE analytical methods (e.g., optimization, discrete event systems, etc.) is used with assistance of one of the many computing tools available for SSE-style projects (e.g., MATLAB, SIMUL8, etc.). The course will close with a final, exploratory project and presentation of an analytical method of the students' choosing and how this is applied to an industry of their choosing. (Not open to seniors or graduate students.) Corequisite: Math 132, Physics 117A or 197. Credit 2 units. EN: TU

E35 ESE 205 Introduction to Engineering Design
A hands-on course where students, divided in groups of two or three, will creatively solve one problem throughout the semester using tools from electrical and systems engineering. The groups choose their own schedule and work under the supervision of an academic team consisting of faculty and higher-level students. The evaluation considers the completion of objectives set by the students with help of the academic team, as well as the originality, innovation, and impact of the project. Prerequisites: CSE 131, Physics 117A or equivalent. Credit 3 units. EN: TU

E35 ESE 230 Introduction to Electrical and Electronic Circuits

E35 ESE 232 Introduction to Electronic Circuits
Analysis and design of linear and nonlinear electronic circuits. Detailed analysis of operational amplifier circuits, including non-ideal characteristics. Terminal characteristics of active semiconductor devices. Incremental and DC models for diodes, metal-oxide-semiconductor field effect transistors (MOSFETs) and bipolar junction transistors (BJTs). Design and analysis of single- and multi-stage amplifiers. Introduction to CMOS logic as well as static and dynamic memory circuits. Students will be required to design, analyze, build and demonstrate several of the circuits studied, including frequency response analysis and use of simulation tools. Prerequisite: ESE 230. Credit 3 units. EN: TU

E35 ESE 260 Introduction to Digital Logic and Computer Design
Introduction to design methods for digital logic and fundamentals of computer architecture. Boolean algebra and logic minimization techniques; sources of delay in combinational circuits and effect on circuit performance; survey of common combinational circuit components; sequential circuit design and analysis; timing analysis of sequential circuits; use of computer-aided design tools for digital logic design (schematic capture, hardware description languages, simulation); design of simple processors and memory subsystems; program execution in simple processors; basic techniques for enhancing processor performance; configurable logic devices. Prerequisite: CSE 131. Same as E81 CSE 260M Credit 3 units. EN: TU
E35 ESE 297 Introduction to ESE Undergraduate Research Projects
This course is offered to students at all levels from all departments. The course is designed to give students some hands-on experience by implementing projects that use the lab PCs, the sbRIO robots from National Instruments, acoustic sensors, bio-medical sensors and 3D cameras. These projects are implemented in LabVIEW and MATLAB and should prepare the students to work on topics that include the Robotic Sensing Undergraduate Research Projects in subsequent semesters. Note that under ESE 497 Undergraduate Research, students may select the Robotic Sensing Projects as well as other projects. Working in groups, students implement algorithms that run on PCs and our wireless robotic platforms to track a moving audio source. Also, they use an EEG system to implement a Brain Computer Interface (BCI) project and work with the new Kinect camera from Microsoft. Corequisite: CSE 131 or equivalent. Credit 3 units.

E35 ESE 318 Engineering Mathematics A
Laplace transforms; matrix algebra; vector analysis; eigenvalues and eigenvectors; vector differential calculus and vector integral calculus in three dimensions. Prerequisites: Math 233 and Math 217 or their equivalents. Credit 3 units.

E35 ESE 319 Engineering Mathematics B
Power series and Frobenius series solutions of differential equations; Legendre’s equation; Bessel’s equation; Fourier series and Fourier transforms; Sturm-Liouville theory; solutions of partial differential equations; wave and heat equations. Prerequisites: Math 233 and Math 217 or their equivalents. Credit 3 units.

E35 ESE 326 Probability and Statistics for Engineering
Study of probability and statistics together with engineering applications. Probability and statistics: random variables, distribution functions, density functions, expectations, means, variances, combinatorial probability, geometric probability, normal random variables, joint distribution, independence, correlation, conditional probability, Bayes theorem, the law of large numbers, the central limit theorem. Applications: reliability, quality control, acceptance sampling, linear regression, design and analysis of experiments, estimation, hypothesis testing. Examples are taken from engineering applications. Prerequisites: Math 233 or equivalent. Credit 3 units. EN: TU

E35 ESE 330 Engineering Electromagnetics Principles
Electromagnetic theory as applied to electrical engineering: vector calculus; electrostatics and magnetostatics; Maxwell’s equations, including Poynting’s theorem and boundary conditions; uniform plane-wave propagation; transmission lines, TEM modes, including treatment of general lossless lines, and pulse propagation; introduction to guided waves; introduction to radiation and scattering concepts. Prerequisites: Physics 118A and ESE 318 En Math A. Corequisite: ESE 319 En Math B. Credit 3 units. EN: TU

E35 ESE 331 Electronics Laboratory
Laboratory exercises provide students with a combination of hands-on experience in working with a variety of real instruments and in summarizing measurement results in written reports that clearly communicate laboratory results. A sequence of lab experiments provide hands-on experience with grounding and shielding techniques, signal analysis, realistic operational amplifier (op amp) characterization, op amp based active filter design and characterization, measurement of pulses propagating on a transmission line with various terminations, experience with FM modulation using phase locked loops and microwave techniques based on the vector network analyzer (VNA). Students will gain experience working with: sampling oscilloscopes to make measurements in the time and frequency domains, signal generators, digital multimeter and frequency measurements, microwave VNA measurements of directional coupler and antenna scattering parameters, and in creating circuits and making connections on contemporary circuit boards. The course concludes with a hands-on project to design, demonstrate and document the design of an electronic component. Prerequisite: ESE 230, ESE 232; Corequisite: ESE 330. Credit 3 units. EN: TU

E35 ESE 332 Power, Energy and Polyphase Circuits
Fundamental concepts of power and energy; electrical measurements; physical and electrical arrangement of electrical power systems; polyphase circuit theory and calculations; principal elements of electrical systems such as transformers, rotating machines, control and protective devices, their description and characteristics; elements of industrial power system design. Prerequisite: ESE 230. Credit 3 units. EN: TU

E35 ESE 337 Electronic Devices and Circuits

E35 ESE 351 Signals and Systems
E35 ESE 362 Computer Architecture
This course explores the interaction and design philosophy of hardware and software for digital computer systems. Topics include: processor architecture, instruction set architecture, assembly language, memory hierarchy design, I/O considerations, and a comparison of computer architectures. Prerequisite: CSE 260M.
Same as E81 ESE 362M.
Credit 3 units. EN: TU

E35 ESE 400 Independent Study
Opportunities to acquire experience outside the classroom setting and to work closely with individual members of the faculty. A final report must be submitted to the department. Not open to first-year or graduate students. Consult adviser. Hours and credit to be arranged.
Credit variable, maximum 3 units.

E35 ESE 401 Fundamentals of Engineering Review
A review and preparation of the most recent NCEES Fundamentals of Engineering (FE) Exam specifications is offered in a classroom setting. Exam strategies will be illustrated using examples. The main topics for the review include: engineering mathematics, statics, dynamics, thermodynamics, heat transfer, mechanical design and analysis, material science and engineering economics. A discussion of the importance and responsibilities of professional engineering licensure along with ethics will be included.
Same as E37 MEMS 4001.
Credit 1 unit.

E35 ESE 403 Operations Research
Introduction to the mathematical aspects of various areas of operations research, with additional emphasis on problem formulation. This is a course of broad scope, emphasizing both the fundamental mathematical concepts involved, and also aspects of the translation of real-world problems to an appropriate mathematical model. Subjects to be covered include linear and integer programming, network problems, and dynamic programming. Prerequisites: CSE 131, Math 309, and ESE 326, or permission of instructor.
Credit 3 units. EN: TU

E35 ESE 404 Applied Operations Research
Application of operations research techniques to real-world problems. Emphasis is given to integer linear programming and computational methods. Real-world examples of integer programs will be studied in areas such as network flow, facility location, partitioning, matching, and transportation. Special emphasis will be placed on techniques used to solve integer programs. Prerequisites: ESE 403 and CSE 131.
Credit 3 units. EN: TU

E35 ESE 405 Reliability and Quality Control
An integrated analysis of reliability and quality control function in manufacturing. Statistical process control, acceptance sampling, process capability analysis, reliability prediction, design, testing, failure analysis and prevention, maintainability, availability, and safety are discussed and related. Qualitative and quantitative aspects of statistical quality control and reliability are introduced in the context of manufacturing. Prerequisite: ESE 326 or equivalent.
Credit 3 units. EN: TU

E35 ESE 407 Analysis and Simulation of Discrete Event Systems
Study of the dynamic behavior of discrete event systems and techniques for analyzing and optimizing the performance of such systems. Covers both classical and recent approaches. Classical topics include Markov chains, queueing theory, networks of queues, related algorithms and simulation methods. Recent approaches include decomposition and aggregation, approximation, and perturbation analysis of nonclassical systems. Applications are drawn from various areas, including production systems. Prerequisites: Math 217, ESE 326 or equivalent, programming experience such as CSE 131 or CSE 200.
Credit 3 units. EN: TU

E35 ESE 415 Optimization
This course gives a rigorous and comprehensive introduction of fundamentals of nonlinear optimization theory and computational methods. Topics include unconstrained and constrained optimization, quadratic and convex optimization, numerical optimization methods, optimality conditions, and duality theory. Algorithmic methods include Steepest Descent, Newton’s method, Conjugate Gradient methods as well as exact and inexact line search procedures for unconstrained optimization. Constrained optimization methods include penalty and multiplier methods. Applications range from engineering and physics to economics. Moreover, generalized programming, interior point methods, and semi-definite programming will be discussed if time permits. Prerequisites: CSE 131, Math 309 and ESE 318 or permission of instructor.
Credit 3 units. EN: TU

E35 ESE 425 Random Processes and Kalman Filtering
Probability and random variables; random processes, autocorrelation, power spectral density; transient and steady-state analysis of linear dynamic systems and random inputs, filters, state-space, discretization; optimal estimation; the discrete Kalman filter; linearization and the extended Kalman filter for nonlinear dynamic systems; related MATLAB exercises. Prerequisite: ESE 326 and ESE 351 or equivalent.
Credit 3 units. EN: TU

E35 ESE 427 Financial Mathematics
This course is a self-contained introduction to financial mathematics at the undergraduate level. Topics to be covered include pricing of the financial instruments such as options, forwards, futures and their derivatives along with basic hedging techniques and portfolio optimization strategies. The emphasis is put on using of discrete, mostly binary models. The general, continuous case including the concepts of Brownian motion, stochastic integral, and stochastic differential equations, is explained from intuitive and practical point of view. Among major results discussed are the Arbitrage Theorem and Black-Scholes differential equations and their solutions. Prerequisites: ESE 318 and ESE 326 or the consent of the instructor.
Credit 3 units. EN: TU

E35 ESE 429 Basic Principles of Quantum Optics and Quantum Information
This course provides an accessible introduction to quantum optics and quantum engineering for undergraduate students. This course covers the following topics: concept of photons,
quantum mechanics for quantum optics, radiative transitions in atoms, lasers, photon statistics (photon counting, Sub-/Super-Poissonian photon statistics, bunching, anti-bunching, theory of photodetection, shot noise), entanglement, squeezed light, atom-photon interactions, cold atoms, atoms in cavities. The course will also provide an overview for quantum information processing: quantum computing, quantum cryptography, and teleportation. Prerequisite: Engineering Mathematics 318 or equivalent.
Credit 3 units. EN: TU

**E35 ESE 433 Radio Frequency and Microwave Technology for Wireless Systems**
Focus is on the components and associated techniques employed to implement analog and digital radio frequency (RF) and microwave (MW) transceivers for wireless applications, including: cell phones; pagers; wireless local area networks; global positioning satellite-based devices; and RF identification systems. A brief overview of system-level considerations is provided, including modulation and detection approaches for analog and digital systems; multiple-access techniques and wireless standards; and transceiver architectures. Focus is on RF and MW: transmission lines; filter design; active component modeling; matching and biasing networks; amplifier design; and mixer design. Prerequisite: ESE 330.
Credit 3 units. EN: TU

**E35 ESE 434 Solid-State Power Circuits and Applications**
Study of the strategies and applications power control using solid-state semiconductor devices. Survey of generic power electronic converters. Applications to power supplies, motor drives and consumer electronics. Introduction to power diodes, thyristors and MOSFETs. Prerequisites: ESE 232, ESE 351.
Credit 3 units. EN: TU

**E35 ESE 435 Electrical Energy Laboratory**
Experimental studies of principles important in modern electrical energy systems. Topics include: AC power measurements, electric lighting, photovoltaic cells and arrays, batteries, DC-DC and DC-AC converters, brushed and brushless DC motors and three-phase circuits. Each experiment requires analysis, simulation with MultiSim, and measurement via LabVIEW and the Elvis II platform. Prerequisites: ESE 230 and 351.
Credit 3 units. EN: TU

**E35 ESE 436 Advanced Electronic Devices**
The physics of state-of-the-art electronic devices. Devices studied include novel diode structures (light-emitting diodes, semiconductor laser diodes), high-power devices (SCRs, TRIACs and power transistors), and high-speed devices. High-speed devices include heterojunction bipolar (HBT), heterojunction field-effect (HFET) and high electron mobility (HEMT) transistors used in very high-speed systems (up to 100 GHz). Advanced bipolar transistors (poly-Si), used in high-speed microprocessors, examined; also materials properties, transport mechanisms, band structure and physics of these devices. Prerequisite: ESE 336.
Credit 3 units. EN: TU

**E35 ESE 437 Sustainable Energy Systems**
We will survey the field of sustainable energy and explore contributions within electrical and systems engineering. Topics include introductory electric power systems, smart grids, and the roles of heat engines, photovoltaics, wind power, and energy storage, as well as analysis and optimization of energy systems. The course will include review and discussion of literature, problem sets, exams, and student projects. Prerequisites: ESE 318 or 319 and ESE 230 or ESE 351 or permission of instructor.
Credit 3 units. EN: TU

**E35 ESE 438 Applied Optics**
Topics relevant to the engineering and physics of conventional as well as experimental optical systems and applications explored. Items addressed include geometrical optics, Fourier optics such as diffraction and holography, polarization and optical birefringence such as liquid crystals, and nonlinear optical phenomena and devices. Prerequisite: ESE 330 or equivalent.
Credit 3 units. EN: TU

**E35 ESE 439 Introduction to Quantum Communications**
This course covers the following topics: quantum optics, single-mode and two-mode quantum systems, nonlinear optics, and quantum systems theory. Specific topics include the following: Dirac notation quantum mechanics; harmonic oscillator quantization; number states, coherent states, and squeezed states; direct, homodyne, and heterodyne detection; linear propagation loss; phase insensitive and phase sensitive amplifiers; entanglement and teleportation; field quantization; quantum photodetector; phase-matched interactions; optical parametric amplifiers; generation of squeezed states, photon-twin beams, non-classical fourth-order interference, and polarization entanglement; optimum binary detection; quantum precision measurements; and quantum cryptography. Prerequisites: ESE 330 or Physics 421; Physics 217 or equivalent.
Credit 3 units. EN: TU

**E35 ESE 441 Control Systems**
Introduction to the theory and practice of automatic control for dynamical systems. Dynamical systems as models for physical and observed phenomena. Mathematical representation of dynamical systems, such as state-space differential and difference equations, transfer functions, and block diagrams. Analysis of the time evolution of a system in response to control inputs, steady-state and transient responses, equilibrium points and their stability. Control via linear state feedback, and estimation using Leunberger observers. Relating the time response of a system to its frequency response, including Bode and Nyquist plots. Input-output stability and its relation to the stability of equilibrium points. Simple frequency-based controllers, such as PID and lead-lag compensators. Exercise involving the use of MATLAB/Simulink (or equivalent) to simulate and analyze systems. Prerequisites: ESE 351 or ESE 355.
Credit 3 units. EN: TU

**E35 ESE 444 Sensors and Actuators**
The course provide engineering students with basic understanding of two of the main components of any modern electrical or electromechanical system; sensors as inputs and actuators as outputs. The covered topics include transfer functions, frequency responses and feedback control. Component matching and bandwidth issue. Performance specification and analysis, Sensors: analog and digital motion sensors, optical sensors, temperature sensors, magnetic and electromagnetic sensors, acoustic sensors, chemical sensors, radiation sensors, torque, force and tactile sensors. Actuators:
stepper motors, DC and AC motors, hydraulic actuators, magnet and electromagnetic actuators, acoustic actuators.

Introduction to interfacing methods: bridge circuits, A/D and D/A converters, microcontrollers. This course is useful for those students interested in control engineering, robotics and systems engineering. Prerequisites: one of the following 4 conditions: (1) prerequisite of ESE 230 and corequisite of ESE 351; (2) prerequisites of ESE 230, ESE 318 and MEMS 255 (Mechanics II); (3) prerequisites of ESE 151 and ESE 351; (4) permission of instructor.

Credit 3 units. EN: TU

E35 ESE 446 Robotics: Dynamics and Control
Homogeneous coordinates and transformation matrices. Kinematic equations and the inverse kinematic solutions for manipulators, the manipulator Jacobian and the inverse Jacobian. General model for robot arm dynamics, complete dynamic coefficients for six-link manipulator. Synthesis of manipulation control, motion trajectories, control of single- and multiple-link manipulators, linear optimal regulator. Model reference adaptive control, feedback control law for the perturbation equations along a desired motion trajectory. Design of the control systems for robotics. Prerequisites: ESE 351, knowledge of a programming language, and ESE 318; Corequisite: ESE 441.

Credit 3 units. EN: TU

E35 ESE 447 Robotics Laboratory
Introduces the students to various concepts such as modeling, identification, model validation and control of robotic systems. The course focuses on the implementation of identification and control algorithms on a two-link robotic manipulator (the so-called pendubot) that will be used as an experimental testbed. Topics include: introduction to the mathematical modeling of robotic systems; nonlinear model, linearized model; identification of the linearized model: input-output and state-space techniques; introduction to the identification of the nonlinear model: energy-based techniques; model validation and simulation; stabilization using linear control techniques; a closer look at the dynamics; stabilization using nonlinear control techniques. Prerequisite: ESE 351 or MEMS 431. Corequisites or Prerequisites: ESE 441 and 446.

Credit 3 units. EN: TU

E35 ESE 448 Systems Engineering Laboratory
Experimental study of real and simulated systems and their control. Identification, input-output analysis, design and implementation of control systems. Noise effects. Design and implementation of control laws for specific engineering problems. Corequisites: ESE 441 and knowledge of a programming language.

Credit 3 units. EN: TU

E35 ESE 449 Digital Process Control Laboratory
Applications of digital control principles to laboratory experiments supported by a networked distributed control system. Lecture material reviews background of real-time programming, data acquisition, process dynamics, and process control. Exercises in data acquisition and feedback control design using simple and advanced control strategies. Experiments in flow, liquid level, temperature, and pressure control. Term project. Prerequisite: ESE 441 or EECE 401 or equivalent. (Prior to FL2015, this course was numbered: E63 433.) Same as E44 EECE 424

Credit 3 units. EN: TU

E35 ESE 455 Quantitative Methods for Systems Biology
Application of computational mathematical techniques to problems in contemporary biology. Systems of linear ordinary differential equations in reaction-diffusion systems, hidden Markov models applied to gene discovery in DNA sequence, ordinary differential equation and stochastic models applied to gene regulation networks, negative feedback in transcription and metabolic pathway regulation. Prerequisites: (1) Math 217 Differential Equations and (2) a programming course and familiarity with MATLAB.

Credit 3 units. EN: TU

E35 ESE 460 Switching Theory
Advanced topics in switching theory as employed in the synthesis, analysis, and design of information processing systems. Combinational techniques: minimization, multiple output networks, state identification and fault detection, hazards, testability and design for test are examined. Sequential techniques: synchronous circuits, machine minimization, optimal state assignment, asynchronous circuits, and built-in self-test techniques. Prerequisite: CSE 260M.

Same as E81 CSE 460T

Credit 3 units. EN: TU

E35 ESE 461 Design Automation for Integrated Circuit Systems
Integrated circuit systems provide the core technology that power today’s most advanced devices and electronics: smart phones, wearable devices, autonomous robots, and cars, aerospace or medical electronics. These systems often consist of silicon microchips made up by billions of transistors and contain various components such as microprocessors, DSPs, hardware accelerators, memories, and I/O interfaces, therefore design automation is critical to tackle the design complexity at the system level. The objectives of this course is to 1) introduce transistor-level analysis of basic digital logic circuits; 2) provide a general understanding of hardware description language (HDL) and design automation tools for very large scale integrated (VLSI) systems; 3) expose students to the design automation techniques used in the best-known academic and commercial systems. Topics covered include device and circuits for digital logic circuits, digital IC design flow, logic synthesis, physical design, circuit simulation and optimization, timing analysis, power delivery network analysis. Assignments include homework, mini-projects, term paper and group project. Prerequisites: ESE 232; ESE 260.

Credit 3 units. EN: TU

E35 ESE 462 Computer Systems Design
Introduction to modern design practices, including the use of FPGA design methodologies. Students use a commercial CAE/CAD system for VHDL-based design and simulation while designing a selected computation system. Prerequisites: CSE 361S and 362M.

Same as E81 CSE 462M

Credit 3 units. EN: TU

E35 ESE 465 Digital Systems Laboratory
Hardware/software co-design; processor interfacing; procedures for reliable digital design, both combinational and sequential; understanding manufacturers’ specifications; use of test
equipment. Several single-period laboratory exercises, several design projects, and application of microprocessors in digital design. One lecture and one laboratory period a week. Prerequisites: ESE 260. Credit 3 units. EN: TU

E35 ESE 467 Embedded Computing Systems
Introduces the issues, challenges and methods for designing embedded computing systems — systems designed to serve a particular application, which incorporate the use of digital processing devices. Examples of embedded systems include PDAs, cellular phones, appliances, game consoles, automobiles and iPod. Emphasis is given to aspects of design that are distinct to embedded systems. The course examines hardware, software and system-level design. Hardware topics include microcontrollers, digital signal processors, memory hierarchy and I/O. Software issues include languages, run-time environments and program analysis. System-level topics include real-time operating systems, scheduling, power management and wireless sensor networks. Students perform a course project on a real wireless sensor network testbed. Prerequisite: CSE 361S. Same as E81 CSE 467S. Credit 3 units. EN: TU

E35 ESE 471 Communications Theory and Systems
Introduction to the concepts of transmission of information via communication channels. Amplitude and angle modulation for the transmission of continuous-time signals. Analog-to-digital conversion and pulse code modulation. Transmission of digital data. Introduction to random signals and noise and their effects on communication. Optimum detection systems in the presence of noise. Elementary information theory. Overview of various communication technologies such as radio, television, telephone networks, data communication, satellites, optical fiber and cellular radio. Prerequisites: ESE 351 and ESE 326. Credit 3 units. EN: TU

E35 ESE 474 Introduction to Wireless Sensor Networks
This is an introductory course on wireless sensor networks for senior undergraduate students. The course uses a combination of lecturing, reading, and discussion of research papers to help each student understand the characteristics and operations of various wireless sensor networks. Topics covered include sensor network architecture, communication protocols on Medium Access Control and Routing, sensor network simulation, sensor data aggregation and dissemination, localization and time synchronization, energy management, and target detection and tracking using acoustic sensor networks. Prerequisite: ESE 351 (Signals and Systems). Credit 3 units. EN: TU

E35 ESE 482 Digital Signal Processing

E35 ESE 488 Signals and Communication Laboratory
Laboratory exercises in digital signal processing, data conversion and communications using modern laboratory techniques and apparatus based on National Instruments LabVIEW and ELVIS II workstations. A laboratory course designed to complement the traditional ESE course offerings in signal processing and communication theory. Signals and systems fundamentals: continuous-time and discrete-time linear time-invariant systems, frequency response, oversampled and noise-shaped A/D conversion, Digital signal processing: FIR and IIR digital filter design, application of the Fast Fourier Transform. Communication theory: baseband, digital communication, amplitude modulation, phase modulation, bandpass digital communication. Laboratory experiments involve analog and digital electronics. Computer workstations and modern computational software used extensively for system simulation and real-time signal processing. Prerequisite: ESE 351. Credit 3 units. EN: TU

E35 ESE 497 Undergraduate Research
Undergraduate research under the supervision of a faculty member. The scope and depth of the research must be approved by the faculty member prior to enrollment. A written final report and a webpage describing the research are required. Credit variable, maximum 3 units.

E35 ESE 498 Electrical Engineering Capstone Design Projects
Capstone design project supervised by the course instructor. The project must use the theory, techniques, and concepts of the student's major: electrical engineering or systems science & engineering. The solution of a real technological or societal problem is carried through completely, starting from the stage of initial specification, proceeding with the application of engineering methods, and terminating with an actual solution. Collaboration with a client, typically either an engineer or supervisor from local industry or a professor or researcher in university laboratories, is encouraged. A proposal, an interim progress update, and a final report are required, each in the forms of a written document and oral presentation, as well as a webpage on the project. Weekly progress reports and meetings with the instructor are also required. Prerequisite: ESE senior standing and instructor's consent. Note: This course will meet at the scheduled time only during select weeks. If you cannot attend at that time, you may still register for the course. Credit 3 units. EN: TU

E35 ESE 499 Systems Science and Engineering Capstone Design Project
Capstone design project supervised by the course instructor. The project must use the theory, techniques, and concepts of the student's major: electrical engineering or systems science & engineering. The solution of a real technological or societal problem is carried through completely, starting from the stage of initial specification, proceeding with the application of engineering methods, and terminating with an actual solution. Collaboration with a client, typically either an engineer or supervisor from local industry or a professor or researcher in university laboratories, is encouraged. A proposal, an interim progress update, and a final report are required, each in the forms of a written document and oral presentation, as well as a webpage on the project. Weekly progress reports and meetings with the instructor are also required. Prerequisite: ESE senior standing and instructor's consent. Note: This course will meet
at the scheduled time only during select weeks. If you cannot
attend at that time, you may still register for the course.
Credit 3 units. EN: TU

E35 ESE 500 Independent Study
Opportunities to acquire experience outside the classroom
setting and to work closely with individual members of the
faculty. A final report must be submitted to the department.
Prerequisite: Students must have the ESE Research/
Independent Study Registration Form (PDF) (https://
es.e.wustl.edu/research/areas/Documents/Independent%20Study%
E35 ESE 514 Calculus of Variations
Introduction to the theory and applications of the calculus of
variations. Theory of functionals; variational problems for an
unknown function; Euler's equation; variable end-point problems;

E35 ESE 515 Nonlinear Optimization
Nonlinear optimization problems with and without constraints
and computational methods for solving them. Optimality
conditions, Kuhn-Tucker conditions, Lagrange duality; gradient
and Newton's methods; conjugate direction and quasi-Newton
methods; primal and penalty methods; Lagrange methods. Use
of MATLAB optimization techniques in numerical problems.
Prerequisites: ESE 318
Credit 3 units.

E35 ESE 516 Optimization in Function Space
Linear vector spaces, normed linear spaces, Lebesque integrals,
the Lp spaces, linear operators, dual space, Hilbert spaces.
Projection theorem, Hahn-Banach theorem. Hyperplanes and
convex sets. Gateaux and Fréchet differentials, unconstrained
minima, adjoint operators, inverse function theorem. Constrained
minima, equality constraints, Lagrange multipliers, calculus of
variations, Euler-Lagrange equations, positive cones, inequality
constraints. Kuhn-Tucker theorem, optimal control theory,
Portyragin's maximum principle, successive approximation
methods, Newton's methods, steepest descent methods, primal-
dual methods, penalty function methods, multiplier methods.
Prerequisite: Math 4111.
Credit 3 units.

E35 ESE 517 Partial Differential Equations
Linear and nonlinear first order equations. Characteristics.
Classification of equations. Theory of the potential linear and
nonlinear diffusion theory. Linear and nonlinear wave equations.
Initial and boundary value problems. Transform methods.
Integral equations in boundary value problems. Prerequisites:
ESE 318 and 319 or equivalent or consent of instructor.
Credit 3 units. EN: TU

E35 ESE 519 Convex Optimization
Concentrates on recognizing and solving convex optimization
problems that arise in applications. Convex sets, functions,
and optimization problems. Basics of convex analysis.
Least-squares, linear and quadratic programs, semidefinite
programming, minimax, extremal volume, and other problems.
Optimality conditions, duality theory, theorems of alternative,
and applications. Interior-point methods. Applications to signal processing, statistics and machine learning, control and mechanical engineering, digital and analog circuit design, and finance. Prerequisites: Math 309 and ESE 415. Credit 3 units.

**E35 ESE 520 Probability and Stochastic Processes**  
Review of probability theory; models for random signals and noise; calculus of random processes; noise in linear and nonlinear systems; representation of random signals by sampling and orthonormal expansions. Poisson, Gaussian and Markov processes as models for engineering problems. Prerequisite: ESE 326. Credit 3 units. EN: TU

**E35 ESE 521 Random Variables and Stochastic Processes I**  
Mathematical foundations of probability theory, including constructions of measures, Lebesque-measure, Lebesque-integral, Banach space property of Lp, basic Hilbert-space theory, conditional expectation. Kolmogorov's theorems on existence and sample-path continuity of stochastic processes. An in-depth look at the Wiener process. Filtrations and stopping times. Markov processes and diffusions, including semigroup properties and the Kolmogorov forward and backward equations. Prerequisites: ESE 520 or equivalent, Math 411. Credit 3 units.

**E35 ESE 522 Information Theory**  
Discrete source and channel model, definition of information rate and channel capacity, coding theorems for sources and channels, encoding and decoding of data for transmission over noisy channels. Corequisite: ESE 520. Credit 3 units. EN: TU

**E35 ESE 523 Detection and Estimation Theory**  

**E35 ESE 524 Network Science**  
This course focuses on fundamental theory, modeling, structure, and analysis methods in network science. The first part of the course includes basic network models and their mathematical principles. Topics include a review of graph theory, random graph models, scale-free network models and dynamic networks. The second part of the course includes structure and analysis methods in network science. Topics include network robustness, community structure, spreading phenomena and clique topology. Applications of the topics covered by this course include social networks, power grid, internet, communications, protein-protein interactions, epidemic control, global trade, neuroscience, etc. Prerequisite courses: ESE 520 (Probability and Stochastic Processes), Math 429 (Linear Algebra) or equivalent. Credit 3 units.

**E35 ESE 529 Special Topics in Information Theory and Applied Probability**  
Credit 3 units.

**E35 ESE 531 Nano and Micro Photonics**  
This course focuses on fundamental theory, design, and applications of photonic materials and micro/nano photonic devices. It includes review and discussion of light-matter interactions in nano and micro scales, propagation of light in waveguides, nonlinear optical effect and optical properties of nano/micro structures, the device principles of waveguides, filters, photodetectors, modulators and lasers. Prerequisite: ESE 330. Credit 3 units. EN: TU

**E35 ESE 532 Introduction to Nano-Photonic Devices**  
Introduction to photon transport in nano-photonic devices. This course focuses on the following topics: light and photons, statistical properties of photon sources, temporal and spatial correlations, light-matter interactions, optical nonlinearity, atoms and quantum dots, single- and two-photon devices, optical devices, and applications of nano-photonic devices in quantum and classical computing and communication. Prerequisites: ESE 330 and Physics 217, or permission of instructor. Credit 3 units. EN: TU

**E35 ESE 534 Special Topics in Advanced Electrodynamics**  
This course covers advanced topics in electrodynamics. Topics include electromagnetic wave propagation (in free space, confined waveguides, or along engineered surfaces); electromagnetic wave scattering (off nano-particles or molecules); electromagnetic wave generation and detection (antenna and nano-antenna); inverse scattering problems; and numerical and approximate methods. Prerequisites: ESE 330, or Physics 421 and Physics 422. Credit 3 units. EN: TU

**E35 ESE 536 Introduction to Quantum Optics**  
This course covers the following topics: quantum mechanics for quantum optics, radiative transitions in atoms, lasers, photon statistics (photon counting, Sub-/Super-Poissionian photon statistics, bunching, anti-bunching, theory of photodetection, shot noise), entanglement, squeezed light, atom-photon interactions, cold atoms, atoms in cavities. If time permits, the following topics are selectively covered: quantum computing, quantum cryptography, and teleportation. Prerequisites: ESE 330 and Physics 217 or Physics 421. Credit 3 units. EN: TU

**E35 ESE 538 Advanced Electromagnetic Engineering**  
The course builds on undergraduate electromagnetics to systematically develop advanced concepts in electromagnetic theory for engineering applications. The following topics are covered: Maxwell's equations; fields and waves in materials; electromagnetic potentials and topics for circuits and systems; transmission-line essentials for digital electronics and for communications; guided wave principles for electronics and optoelectronics; principles of radiation and antennas; and numerical methods for computational electromagnetics. Credit 3 units.
E35 ESE 543 Control Systems Design by State Space Methods
Advanced design and analysis of control systems by state-space methods: classical control review, Laplace transforms, review of linear algebra (vector space, change of basis, diagonal and Jordan forms), linear dynamic systems (modes, stability, controllability, state feedback, observability, observers, canonical forms, output feedback, separation principle and decoupling), nonlinear dynamic systems (stability, Lyapunov methods). Frequency domain analysis of multivariable control systems. State space control system design methods: state feedback, observer feedback, pole placement, linear optimal control. Design exercises with CAD (computer-aided design) packages for engineering problems. Prerequisite: ESE 351 and ESE 441, or permission of instructor. Credit 3 units. EN: TU

E35 ESE 544 Optimization and Optimal Control
Constrained and unconstrained optimization theory. Continuous time as well as discrete-time optimal control theory. Time-optimal control, bang-bang controls and the structure of the reachable set for linear problems. Dynamic programming, the Pontryagin maximum principle, the Hamilton-Jacobi-Bellman equation and the Riccati partial differential equation. Existence of classical and viscosity solutions. Application to time optimal control, regulator problems, calculus of variations, optimal filtering and specific problems of engineering interest. Prerequisites: ESE 551, ESE 552. Credit 3 units. EN: TU

E35 ESE 545 Stochastic Control

E35 ESE 546 Dynamics & Control in Neuroscience & Brain Medicine
This course provides an introduction to systems engineering approaches to modeling, analysis and control of neuronal dynamics at multiple scales. A central motivation is the manipulation of neuronal activity for both scientific and medical applications using emerging neurotechnology and pharmacology. Emphasis is placed on dynamical systems and control theory, including bifurcation and stability analysis of single neuron models and population mean-field models. Synchronization properties of neuronal networks are covered and methods for control of neuronal activity in both oscillatory and non-oscillatory dynamical regimes are developed. Statistical models for neuronal activity are also discussed. An overview of signal processing and data analysis methods for neuronal recording modalities is provided, toward the development of closed-loop neuronal control paradigms. The final evaluation is based on a project or research survey. Prerequisite(s): ESE 553 (or equivalent); ESE 520 (or equivalent); ESE 351 (or equivalent). Credit 3 units. EN: TU

E35 ESE 547 Robust and Adaptive Control
Graduate-level control system design methods for multi-input multi-output systems. Linear optimal-based methods in robust control, nonlinear model reference adaptive control. These design methods are currently used in most industry control system design problems. These methods are designed, analyzed and simulated using MATLAB. Linear control theory (review), robustness theory (Mu Analysis), optimal control and the robust servomechanism, H-infinity optimal control, robust output feedback controls, Kalman filter theory and design, linear quadratic gaussian with loop transfer recovery, the Loop Transfer Recovery method of Lavretsky, Mu synthesis, Lyapunov theory (review), LaSalle extensions, Barbabat's Lemma, model reference adaptive control, artificial neural networks, online parameter estimation, convergence and persistence of excitation. Prerequisite: ESE 543 or ESE 551 or equivalent. Credit 3 units. EN: TU

E35 ESE 549 Special Topics in Control
Credit 3 units.

E35 ESE 551 Linear Dynamic Systems I
Input-output and state-space description of linear dynamic systems. Solution of the state equations and the transition matrix. Controllability, observability, realizations, pole-assignment, observers and decoupling of linear dynamic systems. Prerequisite: ESE 351. Credit 3 units. EN: TU

E35 ESE 552 Linear Dynamic Systems II

E35 ESE 553 Nonlinear Dynamic Systems
State space and functional analysis approaches to nonlinear systems. Questions of existence, uniqueness and stability; Lyapunov and frequency-domain criteria; w-limits and invariance, center manifold theory and applications to stability, steady-state response and singular perturbations. Poincare-Bendixson theory, the van der Pol oscillator, and the Hopf Bifurcation theorem. Prerequisite: ESE 551. Credit 3 units. EN: TU

E35 ESE 554 Advanced Nonlinear Dynamic Systems
E35 ESE 557 Hybrid Dynamic Systems
Theory and analysis of hybrid dynamic systems, which is the class of systems whose state is composed by continuous-valued and discrete-valued variables. Discrete-event systems models and language descriptions. Models for hybrid systems. Conditions for existence and uniqueness. Stability and verification of hybrid systems. Optimal control of hybrid systems. Applications to cyber-physical systems and robotics. Prerequisite: ESE 551.
Credit 3 units. EN: TU

E35 ESE 559 Special Topics in Systems
Credit 3 units.

E35 ESE 560 Computer Systems Architecture I
An exploration of the central issues in computer architecture: instruction set design, addressing and register set design, control unit design, microprogramming, memory hierarchies (cache and main memories, mass storage, virtual memory), pipelining, and bus organization. The course emphasizes understanding the performance implications of design choices, using architecture modeling and evaluation using VHDL and/or instruction set simulation. Prerequisites: CSE 361S and CSE 260M.
Same as E81 CSE 560M
Credit 3 units. EN: TU

E35 ESE 562 Analog Integrated Circuits
This course focuses on fundamental and advanced topics in analog and mixed-signal VLSI techniques. The first part of the course covers graduate-level materials in the area of analog circuit synthesis and analysis. The second part of the course covers applications of the fundamental techniques for designing analog signal processors and data converters. Several practical aspects of mixed-signal design, simulation and testing are covered in this course. This is a project-oriented course, and it is expected that the students apply the concepts learned in the course to design, simulate and explore different circuit topologies. Prerequisites: CSE 260 and ESE 232.
Credit 3 units.

E35 ESE 566A Modern System-on-Chip Design
The System-on-Chip (SoCs) technology is at the core of most electronic systems: smart phones, wearable devices, autonomous robots, and cars, aerospace or medical electronics. In these SoCs, billions of transistors can be integrated on a single silicon chip, containing various components such as microprocessors, DSPs, hardware accelerators, memories, and I/O interfaces. Topics include SoC architectures, design tools and methods, as well as system-level tradeoffs between performance, power consumption, energy efficiency, reliability, and programmability. Students will gain an insight into the early stage of the SoC design process performing the tasks of developing functional specification, partition and map functions onto hardware and/or software, and evaluating and validating system performance. Assignments include hands-on design projects. Open to both graduate and senior undergraduate students. Prerequisite: ESE 461.
Credit 3 units. EN: TU

E35 ESE 567 Computer Systems Analysis
A comprehensive course on performance analysis techniques. The topics include common mistakes, selection of techniques and metrics, summarizing measured data, comparing systems using random data, simple linear regression models, other regression models, experimental designs, factorial designs with replication, fractional factorial designs, one factor experiments, two factor full factorial design w/o replications, two factor full factorial designs with replications, general full factorial designs, introduction to queueing theory, analysis of single queues, queueing networks, operational laws, mean-value analysis, time series analysis, heavy tailed distributions, self-similar processes, long-range dependence, random number generation, analysis of simulation results, and art of data presentation. Prerequisites: CSE 260M.
Same as E81 CSE 567M
Credit 3 units. EN: TU

E35 ESE 569 Parallel Architectures and Algorithms
Several contemporary parallel computer architectures are reviewed and compared. The problems of process synchronization and load balancing in parallel systems are studied. Several selected applications problems are investigated and parallel algorithms for their solution are considered. Selected parallel algorithms are implemented in both a shared memory and distributed memory parallel programming environment. Prerequisites: graduate standing and knowledge of the C programming language.
Same as E81 CSE 569M
Credit 3 units. EN: TU

E35 ESE 570 Coding Theory
Credit 3 units. EN: TU

E35 ESE 571 Transmission Systems and Multiplexing
Transmission and multiplexing systems are essential to providing efficient point-to-point communication over distance. This course introduces the principles underlying modern analog and digital transmission and multiplexing systems and covers a variety of system examples.
Credit 3 units. EN: TU

E35 ESE 572 Signaling and Control in Communication Networks
The operation of modern communications networks is highly dependent on sophisticated control mechanisms that direct the flow of information through the network and oversee the allocation of resources to meet the communication demands of end users. This course covers the structure and operation of modern signaling systems and addresses the major design trade-offs that center on the competing demands of performance and service flexibility. Specific topics covered include protocols and algorithms for connection establishment and transformation, routing algorithms, overload and failure recovery and networking dimensioning. Case studies provide concrete examples and reveal the key design issues. Prerequisites: graduate standing and permission of instructor.
Credit 3 units. EN: TU

E35 ESE 575 Fiber-Optic Communications
Introduction to optical communications via glass-fiber media. Pulse-code modulation and digital transmission methods, coding
### E35 ESE 581 Radar Systems
Credit 3 units. EN: TU

### E35 ESE 582 Fundamentals and Applications of Modern Optical Imaging
Analysis, design and application of modern optical imaging systems with emphasis on biological imaging. First part of the course focuses on the physical principles underlying the operation of imaging systems and their mathematical models. Topics include ray optics (speed of light, refractive index, laws of reflection and refraction, plane surfaces, mirrors, lenses, aberrations), wave optics (amplitude and intensity, frequency and wavelength, superposition and interference, interferometry), Fourier optics (space-invariant linear systems, Huygens-Fresnel principle, angular spectrum, Fresnel diffraction, Fraunhofer diffraction, frequency analysis of imaging systems), and light-matter interaction (absorption, scattering, dispersion, fluorescence). Second part of the course compares modern quantitative imaging technologies including, but not limited to, digital holography, computational imaging, and super-resolution microscopy. Students evaluate and critique recent optical imaging literature. Prerequisites: ESE 318 and ESE 319 or their equivalents; ESE 330 or Physics 421 or equivalent.
Credit 3 units. EN: TU

### E35 ESE 584 Statistical Signal Processing for Sensor Arrays
Methods for signal processing and statistical inference for data acquired by an array of sensors, such as those found in radar, sonar and wireless communications systems. Multivariate statistical theory with emphasis on the complex multivariate normal distribution. Signal estimation and detection in noise with known statistics, signal estimation and detection in noise with unknown statistics, direction finding, spectral spatial estimation, beam forming, parametric maximum-likelihood techniques. Subspace techniques, including MUSIC and ESPRIT. Performance analysis of various algorithms. Advanced topics may include structured covariance estimation, wideband array processing, array calibration, array processing with polarization diversity, and space-time adaptive processing (STAP). Prerequisites: ESE 520, ESE 524, linear algebra, computer programming.
Credit 3 units. EN: TU

### E35 ESE 588 Quantitative Image Processing
Introduction to modeling, processing, manipulation and display of images. Application of two-dimensional linear systems to image processing. Two-dimensional sampling and transform methods.

Credit 3 units. EN: TU

### E35 ESE 589 Biological Imaging Technology
This class develops a fundamental understanding of the physics and mathematical methods that underlie biological imaging and critically examine case studies of seminal biological imaging technology literature. The physics section examines how electromagnetic and acoustic waves interact with tissues and cells, how waves can be used to image the biological structure and function, image formation methods, and diffraction limited imaging. The math section examines image decomposition using basis functions (e.g., Fourier transforms), synthesis of measurement data, image analysis for feature extraction, reduction of multidimensional imaging datasets, multivariate regression, and statistical image analysis. Original literature on electron, confocal and two photon microscopy, ultrasound, computed tomography, functional and structural magnetic resonance imaging and other emerging imaging technology are critiqued.
Credit 3 units. EN: TU

### E35 ESE 590 Electrical & Systems Engineering Graduate Seminar
This pass/fail course is required for the MS, DSc and PhD degrees in Electrical & Systems Engineering. A passing grade is required for each semester of enrollment and is received by attendance at regularly scheduled ESE seminars. MS students must attend at least three seminars per semester. DSc and PhD students must attend at least five seminars per semester. Part-time students are exempt except during their year of residency. Any student under continuing status is also exempt. Seminars missed in a given semester may be made up during the subsequent semester.

### E35 ESE 596 Seminar in Imaging Science and Engineering
This seminar course consists of a series of tutorial lectures on Imaging Science and Engineering with emphasis on applications of imaging technology. Students are exposed to a variety of imaging applications that vary depending on the semester, but may include multispectral remote sensing, astronomical imaging, microscopic imaging, ultrasound imaging and tomographic imaging. Guest lecturers come from several parts of the university. This course is required of all students in the Imaging Science and Engineering program; the only requirement is attendance. This course is graded pass/fail. Prerequisite: admission to Imaging Science and Engineering program. Same as CSE 596 (when offered) and BME 506.
Credit 1 unit.

### E35 ESE 599 Master's Research
Prerequisite: Students must have the ESE Research/Independent Study Registration Form (PDF) (https://ese.wustl.edu/research/areas/Documents/Independent%20Study%20Form_1.pdf) approved by the department.
Credit variable, maximum 3 units.