Electrical & Systems Engineering

The Department of Electrical & Systems Engineering offers doctoral-level and master’s-level degrees in Electrical Engineering and in Systems Science & Mathematics. At the doctoral level, both the PhD and DSc degrees are available, which typically require four to five years of full-time study leading to an original research contribution. At the master’s level, the programs require 30 credit hours of study and have both a course option and a thesis option.

Research activity in the department is focused in the following four areas:

**Applied Physics**
- Nanophotonics
- Quantum optics
- Engineered materials
- Electrodynamics

**Devices & Circuits**
- Computer engineering
- Integrated circuits
- Radiofrequency circuits
- Sensors

**Systems Science**
- Optimization
- Applied mathematics
- Control
- Financial engineering

**Signals & Imaging**
- Computational imaging
- Signal processing
- Optical imaging
- Data sciences

Students working in any of these areas will enjoy the benefits of programs that balance fundamental theoretical concepts with modern applications. In our department, students find ample opportunities for close interactions with faculty members working on cutting-edge research and technology development.

Prospective PhD students with previous degrees in engineering who are interested in PhD studies and research in mathematics or statistics are encouraged to apply for PhD studies in Mathematics and Statistics. For more details, visit the Graduate Programs in Mathematics and Statistics (http://wumath.wustl.edu/graduate) webpage.

**Faculty**

**Chair**

R. Martin Arthur (https://engineering.wustl.edu/Profiles/Pages/Martin-Arthur.aspx)
Newton R. and Sarah Louisa Glasgow Wilson Professor of Engineering
PhD, University of Pennsylvania
Ultrasonic imaging, electrocardiography

**Endowed Professors**

Arye Nehorai (https://engineering.wustl.edu/Profiles/Pages/Arye-Nehorai.aspx)
Eugene and Martha Lohman Professor of Electrical Engineering
PhD, Stanford University
Statistical signal processing, machine learning, imaging, biomedicine

Joseph A. O’Sullivan (https://engineering.wustl.edu/Profiles/Pages/Joseph-OSullivan.aspx)
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 (https://engineering.wustl.edu/Profiles/Pages/Lan-Yang.aspx)
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 (https://ese.wustl.edu/faculty/Pages/default.aspx?bio=101)
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 (https://engineering.wustl.edu/Profiles/Pages/Hiro-Mukai.aspx)
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 (https://engineering.wustl.edu/Profiles/Pages/Heinz-Schaettler.aspx)
PhD, Rutgers University
Optimal control, nonlinear systems, mathematical models in biomedicine

Associate Professors

Jr-Shin Li (https://engineering.wustl.edu/Profiles/Pages/Jr-Shin-Li.aspx)
Das Family Distinguished Career Development Associate Professor
PhD, Harvard University
Mathematical control theory, optimization, quantum control, biomedical applications

ShiNung Ching (https://engineering.wustl.edu/Profiles/Pages/ShiNung-Ching.aspx)
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 (https://engineering.wustl.edu/Profiles/Pages/Zachary-Feinstein.aspx)
PhD, Princeton University
Financial engineering, operations research, variational analysis

Ulugbek Kamilov (https://ese.wustl.edu/faculty/Pages/default.aspx?bio=120)
PhD, École Polytechnique Fédérale de Lausanne, Switzerland
Computational imaging, signal processing, biomedical imaging

Matthew D. Lew (https://engineering.wustl.edu/Profiles/Pages/Matthew-Lew.aspx)
PhD, Stanford University
Microscopy, biophotonics, computational imaging, nano-optics

Jung-Tsung Shen (https://engineering.wustl.edu/Profiles/Pages/Jung-Tsung-Shen.aspx)
Das Family Distinguished Career Development Assistant Professor
PhD, Massachusetts Institute of Technology
Theoretical and numerical investigations on nanophotonics, optoelectronics, plasmonics, metamaterials

Chuan Wang (https://ese.wustl.edu/faculty/Pages/default.aspx?bio=123)
PhD, University of Southern California
Flexible electronics, stretchable electronics, printed electronics, nanomaterials, nanoelectronics, optoelectronics

Shen Zeng (https://ese.wustl.edu/faculty/Pages/default.aspx?bio=121)
PhD, University of Stuttgart
Systems and control theory, data-based analysis and control of complex dynamical systems, inverse problems, biomedical applications

Xuan “Silvia” Zhang (https://engineering.wustl.edu/Profiles/Pages/Xuan-%28Silvia%29-Zhang.aspx)
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

Assistant Professors

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, electrophysics, 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

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

Degree Requirements

The Department of Electrical & Systems Engineering offers doctoral-level and master's-level degrees in Electrical Engineering and in Systems Science & Mathematics as well as a certificate in Imaging Science. At the doctoral level, both the PhD and DSc degrees are available, which typically require four to five years of full-time study leading to an original research contribution. At the master's level, the programs require a minimum of 30 credit hours of study consistent with the residency and other applicable requirements of Washington University and the School of Engineering & Applied Science. The Master's degrees may be pursued with a course only or thesis option.

Students will enjoy the benefits of programs that balance fundamental theoretical concepts with modern applications. In our department, students find ample opportunities for close interactions with faculty members working on cutting-edge research and technology development.

Please visit the following pages for information about

- Doctoral Degrees (http://bulletin.wustl.edu/grad/engineering/electrical/doctoral-degrees)
- MS in Electrical Engineering (MSEE) (http://bulletin.wustl.edu/grad/engineering/electrical/ms-electrical)
- MS in Data Analytics and Statistics (MSDAS) (http://bulletin.wustl.edu/grad/engineering/electrical/ms-data-analytics-statistics)
- Master of Control Engineering (MCEng) (http://bulletin.wustl.edu/grad/engineering/electrical/ms-data-analytics-statistics)
- Master of Engineering in Robotics (MEngR) (http://bulletin.wustl.edu/grad/engineering/electrical/mceng-control)

Courses

Visit online course listings to view semester offerings for E35 ESE (https://courses.wustl.edu/CourseInfo.aspx?sch=E&dept=E35&crslvl=5:8).

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://ese.wustl.edu/research/areas/Documents/Independent%20Study%20Form_1.pdf) approved by the department.
Credit variable, maximum 3 units.

E35 ESE 501 Mathematics of Modern Engineering I

Matrix algebra: systems of linear equations, vector spaces, linear independence and orthogonality in vector spaces, eigenvectors and eigenvalues; vector calculus: gradient, divergence, curl, line and surface integrals, theorems of Green, Stokes, and Gauss; Elements of Fourier analysis and its applications to solving some classical partial differential equations, heat, wave, and Laplace equation. Prerequisites: ESE 318 and ESE 319 or equivalent or
E35 ESE 502 Mathematics of Modern Engineering II
Fourier series and Fourier integral transforms and their applications to solving some partial differential equations, heat and wave equations; complex analysis and its applications to solving real-valued problems: analytic functions and their role, Laurent series representation, complex-valued line integrals and their evaluation including the residual integration theorem, conformal mappings and their applications. Prerequisites: ESE 318 and ESE 319 or ESE 317 or equivalent, or consent of instructor. This course will not count toward the ESE doctoral program.
Credit 3 units. EN: TU

E35 ESE 512 Advanced Numerical Analysis
Special topics chosen from numerical solution of partial differential equations, uniform and least-squares approximation spline approximation, Galerkin methods and finite element approximation, functional analysis applied to numerical mathematics, and other topics of interest. Prerequisite: ESE 511 or consent of instructor.
Credit 3 units. EN: TU

E35 ESE 513 Convex Optimization and Duality Theory
Graduate introduction to convex optimization with emphasis on convex analysis and duality theory. Topics include: convex sets, convex functions, convex cones, convex conjugates, Fenchel-Moreau theorem, convex duality and biconjugation, directional derivatives, subgradients and subdifferentials, optimality conditions, ordered vector spaces, Hahn-Banach theorem, extension and separation theorems, minimax theorems, and vector and set optimization. Prerequisites: ESE 415, Math 4111.
Credit 3 units.

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; variational problems with subsidiary conditions; sufficient conditions for extrema; applications to optimum control and/or to other fields. A term project is required. Prerequisites: ESE 318 and 319 or ESE 317 or equivalent.
Credit 3 units.

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: CSE 131, Math 309 and ESE 318 or permission of instructor.
Credit 3 units. EN: TU

E35 ESE 516 Optimization in Function Space
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 518 Optimization Methods in Control
The course is divided in two parts: convex optimization and optimal control. In the first part we cover applications of Linear Matrix Inequalities and Semi-Definite Programming to control and estimation problems. We also cover Multivariate Linear Programming and its application to the Model Predictive Control and Estimation of linear systems. In the second part we cover numerical methods to solve optimal control and estimation problems. We cover techniques to discretize optimal control problems, numerical methods to solve them, and their optimality conditions. We apply these results to the Model Predictive Control and Estimation of nonlinear systems. Prerequisites: ESE 551, and ESE 415 or equivalent.
Credit 3 units. EN: TU

E35 ESE 519 Convex Optimization
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, Lebesgue-measure, Lebesgue-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
E35 ESE 523 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 524 Detection and Estimation Theory

E35 ESE 526 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. EN: TU

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.

E35 ESE 533 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-Poissonian 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 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 Advanced Electromagnetic Engineering
This 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 538 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 543 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 Hamiltonian-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
Credit 3 units. EN: TU

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, Barbilat'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
Credit 3 units. EN: TU

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
Credit 3 units.

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 (SoC) 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, 2**k 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
Introduction to the algebra of finite fields. Linear block codes, cyclic codes, BCH and related codes for error detection and correction. Encoder and decoder circuits and algorithms. Spectral descriptions of codes and decoding algorithms. Code performances. 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 laws, receivers, bit-error rates. Types and properties of optical fibers; attenuation, dispersion, modes, numerical aperture. Light-emitting diodes and semiconductor laser sources; device structure, speed, brightness, modes, electrical properties, optical and spectral characteristics. Prerequisites: ESE 330, ESE 336. Credit 3 units. EN: TU

E35 ESE 581 Radar Systems

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.

**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, spatial spectrum 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, wide-band 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.

**E35 ESE 588 Quantitative Image Processing**
Credit 3 units.

**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.

**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) approved by the department. Credit variable, maximum 3 units.

**E35 ESE 600 Doctoral Research**
Credit variable, maximum 9 units.

**E35 ESE 883 Master’s Continuing Student Status**