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; these 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 units 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**
Bruno Sinopoli (https://engineering.wustl.edu/Profiles/Pages/Bruno-Sinopoli.aspx)
Das Family Distinguished Professor
PhD, University of California, Berkeley
Cyberphysical systems, analysis and design of networked embedded control systems, with applications to sensor actuators networks

**Endowed Professors**
Shantanu Chakrabartty (https://engineering.wustl.edu/faculty/Shantanu-Chakrabartty.html)
Clifford W. Murphy Professor
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

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

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/faculty/Lan-Yang.html)
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

Phone: 314-935-5565
Website: https://ese.wustl.edu/academics/graduate-programs/index.html

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Professors

Jr-Shin Li (https://engineering.wustl.edu/faculty/Jr-Shin-Li.html)
Professor
PhD, Harvard University
Mathematical control theory, optimization, quantum control, biomedical applications

Neal Patwari (https://engineering.wustl.edu/faculty/Neal-Patwari.html)
Professor
PhD, University of Michigan
Intersection of statistical signal processing and wireless networking for improving wireless sensor networking and radiofrequency sensing

Associate Professors

ShiNung Ching (https://engineering.wustl.edu/faculty/ShiNung-Ching.html)
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

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

Assistant Professors

Ulugbek Kamilov (https://engineering.wustl.edu/faculty/Ulugbek-Kamilov.html)
PhD, École Polytechnique Fédérale de Lausanne, Switzerland
Computational imaging, signal processing, biomedical imaging

Mark Lawrence
PhD, University of Birmingham
Nanophotonics, nonlinear optics, metasurfaces

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

PhD, University of Southern California
Flexible electronics, stretchable electronics, printed electronics, nanomaterials, nanoelectronics, optoelectronics

Yong Wang (https://engineering.wustl.edu/faculty/Yong-Wang.html)
PhD, Washington University in St. Louis
Biomedical engineering, life science, human physiology, magnetic resonance imaging, electrocardiographic imaging

Shen Zeng (https://engineering.wustl.edu/faculty/Shen-Zeng.html)
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/faculty/Xuan-Silvia-Zhang.html)
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

Senior Professors

Paul S. Min (https://engineering.wustl.edu/faculty/Paul-Min.html)
PhD, University of Michigan
Routing and control of telecommunication networks, fault tolerance and reliability, software systems, network management

DSc, Washington University in St. Louis
Computer engineering, lower-power VLSI design, computer architecture, signal processing, microprocessors systems design

Hiro Mukai (https://engineering.wustl.edu/faculty/Hiro-Mukai.html)
PhD, University of California, Berkeley
Theory and computational methods for optimization, optimal control, systems theory, electric power system operations, differential games

William F. Pickard (https://engineering.wustl.edu/faculty/William-Pickard.html)
PhD, Harvard University
Biological transport, electrophysiology, energy engineering

PhD, Case Western Reserve University
Optoelectronics and fiber optics, semiconductor materials, light-emitting diodes and lasers, semiconductor processing, electronics

Ervin Y. Rodin (https://engineering.wustl.edu/faculty/Ervin-Rodin.html)
PhD, University of Texas at Austin
Optimization, differential games, artificial intelligence, mathematical modeling
Teaching Professor

James Feher (https://engineering.wustl.edu/faculty/James-Feher.html)
PhD, Missouri University of Science and Technology
Electrical engineering, computer science, mathematics and physics

Senior Lecturers

Martha Hasting (https://engineering.wustl.edu/faculty/Martha-Hasting.html)
PhD, Saint Louis University
Mathematics education

Vladimir Kurenok (https://engineering.wustl.edu/faculty/Vladimir-Kurenok.html)
PhD, Belarus State University (Minsk, Belarus)
Probability and stochastic processes, stochastic ordinary and partial differential equations, financial mathematics

PhD, University of Miami
Modeling and performance analysis of wireless sensor networks, multi-source information fusion, ambiguous and incomplete information processing

Lecturers

Tsitsi Madziwa-Nussinov (https://engineering.wustl.edu/faculty/Tsitsi-Nussinov.html)
PhD, University of California, Los Angeles
Fiber optic sensing and practical experience in sensor implementation and field test

Professors Emeriti

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

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; these 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 units of study consistent with the residency and other applicable requirements of Washington University and McKelvey School of Engineering. The master's degrees may be pursued with a course-only option or a thesis option.

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Please visit the following pages for more information about our programs:

- Doctoral Degrees (http://bulletin.wustl.edu/grad/engineering/electrical-and-systems/doctoral-degrees/)
- Master of Science in Electrical Engineering (MSEE) (http://bulletin.wustl.edu/grad/engineering/electrical-and-systems/ms-electrical/)
- Master of Science in Engineering Data Analytics and Statistics (MSDAS) (http://bulletin.wustl.edu/grad/engineering/electrical-and-systems/ms-data-analytics-statistics/)
- Master of Science (MS) in Computer Engineering (http://bulletin.wustl.edu/grad/engineering/electrical-and-systems/ms-computer-engineering/)
- Certificate in Controls (http://bulletin.wustl.edu/grad/engineering/electrical-and-systems/certificate-controls/)

**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 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 consent of instructor. This course will not count toward the ESE doctoral program.

Credit 3 units. EN: BME T, TU

**E35 ESE 502 Mathematics of Modern Engineering II**

This course covers Fourier series and Fourier integral transforms and their applications to solving some partial differential equations and heat and wave equations. It also presents complex analysis and its applications to solving real-valued problems, including analytic functions and their role, Laurent series representation, complex-valued line integrals and their evaluation (including the residual integration theory), and conformal mappings and their applications. Prerequisites: ESE 318 and ESE 319 or equivalent, or permission of instructor. This course will not count toward the ESE doctoral program.

Credit 3 units. EN: BME T, TU

**E35 ESE 513 Large-Scale Optimization for Data Science**

Large-scale optimization is an essential component of modern data science, artificial intelligence, and machine learning. This graduate-level course rigorously introduces optimization methods that are suitable for large-scale problems arising in these areas. Students will learn several algorithms suitable for both smooth and nonsmooth optimization, including gradient methods, proximal methods, mirror descent, Nesterov’s acceleration, ADMM, quasi-Newton methods, stochastic optimization, variance reduction, and distributed optimization. Throughout the course, we will discuss the efficacy of these methods in concrete data science problems, under appropriate statistical models. Students will be required to program in Python or MATLAB. Prerequisites: CSE 247, Math 309, Math 3200, or ESE 326.

Credit 3 units. EN: TU

**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**

**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.

**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: BME T, TU

**E35 ESE 519 Convex Optimization**

**E35 ESE 520 Probability and Stochastic Processes**
This course covers a 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; and Poisson, Gaussian, and Markov processes as models for engineering problems. Prerequisite: ESE 326. Credit 3 units. EN: BME T, TU

**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: BME T, 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 network analysis 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. Prerequisites: ESE 520 (Probability and Stochastic Processes), Math 429 (Linear Algebra) or equivalent. Credit 3 units.

**E35 ESE 527 Practicum in Data Analytics & Statistics**
In this course, students will learn through hands-on experience the application of analytics to support data-driven decisions. Through lectures and the execution of a project (to be defined at the beginning of the semester), students will learn to use descriptive, predictive, and prescriptive analytics. Lectures will focus on presenting analytic topics relevant to the execution of the project, including analytic model development, data quality and data models, review of machine learning algorithms (unsupervised, supervised, and semi-supervised approaches) model validation, insights generation and results communication, and code review and code repository. Students are expected to demonstrate the application of these concepts through the execution of a one-semester project. Students can propose their own projects or choose from a list of projects made available by the lecturer. Projects should reflect real-world problems with a clear value proposition. Progress will be evaluated and graded periodically during the semester, and the course will include a final presentation open to the academic community. Prerequisites: ESE 520 (or Math 493 and 494), ESE 417 or CSE 417T, ESE 415, and declaration of the MS in DAS. Credit 3 units. EN: BME T, TU

**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: BME T, 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: BME T, 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-Poissonian photon statistics, bunching, anti-bunching, theory of photodetection, shot noise), entanglement, squeezed light, atom-photon interactions, cold atoms, and atoms in cavities. Time permits, the following topics will be selectively covered: quantum computing, quantum cryptography, and teleportation. Prerequisites: ESE 330 and Physics 217 or Physics 421. Credit 3 units. EN: BME T, 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: BME T, 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 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.

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. Prerequisites: ESE 553 (or equivalent); ESE 520 (or equivalent); ESE 351 (or equivalent). Credit 3 units. EN: BME T, 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, Barbalat'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: BME T, TU

E35 ESE 551 Linear Dynamic Systems I
Input-output and state-space description of linear 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: BME T, 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-Bendixon theory, the van der Pol oscillator, and the Hopf Bifurcation theorem. Prerequisite: ESE 551. Credit 3 units. EN: BME T, TU

E35 ESE 554 Advanced Nonlinear Dynamic Systems

E35 ESE 555 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: BME T, TU

E35 ESE 556 Analog Integrated Circuits
This course focuses on fundamental and advanced topics in analog signal processors and data converters. Several practical aspects of mixed-signal design, simulation and testing are covered in this course. 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 E91 ESE 566M. Credit 3 units. EN: BME T, TU

E35 ESE 558 Special Topics in Systems and Control
This course provides a rigorous introduction to recent developments in systems and controls. Focus is on the discussion of interdisciplinary applications of complex systems that motivate emerging topics in dynamics and control as well as state-of-the-art methods for addressing the control and computation problems involving these large-scale systems. Topics to be covered include the control of ensemble systems, pseudospectral approximation and high-dimensional optimization, the mathematics of networks, dynamic learning and topological data analysis, and applications to biology, neuroscience, brain medicine, quantum physics, and complex networks. Both model-based and data-driven approaches are introduced. Students learn about state-of-the-art research in the field, and they ultimately apply their knowledge to conduct a final project. Prerequisites: Math 429 or equivalent, ESE 415, ESE 551, ESE 553, and ESE 520. Credit 3 units. EN: TU

E35 ESE 5591 Special Topics in Engineering and Neuroscience
Credit 2 units. EN: TU

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: ESE 361S and ESE 260M. Credit 3 units. EN: BME T, TU

E35 ESE 562 Modern System-on-Chip Design
The System-on-Chip (SoC) technology is at the core of most electronic systems: smartphones, wearable devices, autonomous robots and cars, and aerospace and 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 trade-offs between performance, power consumption, energy efficiency, reliability, and programmability. Students will gain an insight into the early stages of the SoC design process by performing the tasks of developing functional specifications, applying partitions and map functions to hardware and/or software, and then evaluating and validating system performance. Assignments include hands-on design projects. This course is open to both graduate and senior undergraduate students. Prerequisite: ESE 461. Credit 3 units. EN: BME T, TU

E35 ESE 565 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: BME T, 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: BME T, 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: BME T, 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. The first part of the course will focus 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). The second part of the course will compare modern quantitative imaging technologies, including but not limited to digital holography, computational imaging, and super-resolution microscopy. Students will evaluate and critique recent optical imaging literature. Prerequisites: ESE 318 and ESE 319 (or their equivalents); ESE 330 or PHY 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 communication 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. EN: TU

E35 ESE 585A Sparse Modeling for Imaging and Vision
Sparse modeling is at the heart of modern imaging, vision, and machine learning. It is a fascinating new area of research that seeks to develop highly effective data models. The core idea in sparse modeling theory is a novel redundant transform, where the number of transform coefficients is larger compared to the original data dimension. Together with redundancy comes an opportunity for seeking the sparsest possible representation or the one with the fewest non-zeros. This core idea leads to a series of beautiful theoretical and practical results with many applications, such as regression, prediction, restoration, extrapolation, compression, detection, and recognition. In this course, we will explore sparse modeling by covering theoretical as well as algorithmic aspects with applications in computational imaging and computer vision. Prerequisites: ESE 318, Math 233, Math 309, and Math 429 (or equivalents), as well as coding experience with MATLAB or Python.
Credit 3 units. EN: BME T, TU

E35 ESE 588 Quantitative Image Processing
Credit 3 units. EN: BME T, 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: BME T, TU

E35 ESE 590 Electrical & Systems Engineering Graduate Seminar
This satisfactory/unsatisfactory course is required for the master’s, DSc, and PhD degrees in Electrical & Systems Engineering. A satisfactory grade is required for each semester of enrollment, and this is achieved by student attendance at regularly scheduled seminars. Master’s students must attend at least three seminars per semester, except for first-year master’s students, who must attend four. DSc and PhD students must attend at least five seminars per semester, except for first-year PhD students who must attend six. Part-time students are exempt except during their year of residency. Any student under continuing status is also exempt.

Credit 3 units. EN: TU

E35 ESE 591 Biomedical Optics I: Principles
This course covers the principles of optical photon transport in biological tissue. This course covers the principles and applications of optical photon transport in biological tissue. Topics include a brief introduction to biomedical optics, single-scatterer theories, Monte Carlo modeling of photon transport, convolution for broad-beam responses, radiative transfer equation, diffusion theory and applications, sensing of optical properties and spectroscopy, and photoacoustic imaging principles and applications. Prerequisite: Differential equations

Same as E62 BME 591
Credit 3 units. EN: TU

E35 ESE 5931 Mathematics of Imaging Science
This course will expose students to a unified treatment of the mathematical properties of images and imaging. This will include an introduction to linear vector space theory, operator theory on Hilbert spaces, and concepts from applied functional analysis. Concepts from generalized functions, Fourier analysis, and radon transform will also be discussed. These tools will be applied to conduct deterministic analyses of imaging systems that are described as continuous-to-continuous, continuous-to-discrete, and discrete-to-discrete mappings from object properties to image data. In addition, imaging systems will be analyzed in a statistical framework in which stochastic models for objects and images will be introduced. Prerequisite: Senior standing or permission of instructor.

Same as E62 BME 570
Credit 3 units.

E35 ESE 5932 Computational Methods for Imaging Science
Inverse problems are ubiquitous in science and engineering, and they form the basis for modern imaging methods. This course will introduce students to the mathematical formulation of inverse problems and modern computational methods employed to solve them. Specific topics covered will include regularization theory, compressive sampling, variational calculus, and a survey of relevant numerical optimization methods. The application of these methods to tomographic imaging problems will be addressed in detail. Prerequisite: ESE 5931 or permission of instructor.

Credit 3 units. EN: TU

E35 ESE 5933 Theoretical Imaging Science
Imaging science encompasses the design and optimization of imaging systems to quantitatively measure information of interest. Imaging systems are important in many scientific and medical applications and may be designed for one specific application or for a range of applications. Performance is quantified for any given task through an understanding of the statistical model for the imaging data, the data processing algorithm used, and a measure of accuracy or error. Optimal processing is based on statistical decision theory and estimation theory; performance bounds include the receiver operating characteristic and Cramer-Rao bounds. Bayesian methods often lead to ideal observers. Extensions of methods from finite-dimensional spaces to function space are fundamental for many imaging applications. A variety of methods to assess image quality and resulting imaging system optimization are covered. Prerequisite: permission of instructor.

Credit 3 units. EN: TU

E35 ESE 5934 Practicum in Imaging Science
Students develop research results in computational imaging and write a conference paper on the results. This course involves the process of research project design and implementation in imaging science, participation in research teams, the development of milestones for a project, and the process of meeting expectations. The role of machine learning, computational methods, theoretical methods, datasets, and experiments in imaging science research are covered. Prerequisite: Permission of instructor.

Credit 3 units.

E35 ESE 5936 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.

E35 ESE 600 Doctoral Research
Credit variable, maximum 9 units.
E35 ESE 601 Research Rotation for ESE Doctoral Students
Doctoral students in Electrical and Systems Engineering are required to complete two rotations during their first year and may complete three rotations, with research mentors acceptable to the department. The rotations must be mutually agreeable to both the student and the faculty member. The grade will be assigned based on a written report from one of the rotations. The rotations allow students to sample different research projects and laboratory working environments and to enable the matching of doctoral students with the research mentors with whom they will carry out PhD dissertation research. Credit 3 units.

E35 ESE 883 Master's Continuing Student Status