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

E35 ESE 5001 Research Rotation for ESE Masters Students
Masters students in Electrical and Systems Engineering may complete a rotation their first semester with research mentors acceptable to the Department. The rotations must be mutually agreeable to both the student and faculty member. Opportunities to work closely with individual members of the faculty. A final report must be submitted to the department. Prerequisite: ESE 417 or CSE 417T, ESE 415, and declaration of the MS in DAS. Credit 3 units. EN: BME T, TU

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 theorem), 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), ESE 415. Credit 3 units. EN: TU

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 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: BME T, TU

E35 ESE 524 Detection and Estimation Theory

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 5331 Nanophotonic Optical Media — From Metamaterials to Photonic Crystals and Beyond
The nanometer length scale holds a unique significance for optical engineering because it is home to the wavelengths of visible and infrared light. The behavior of a light wave is particularly sensitive to structural features formed at or below the scale of its wavelength and, as a consequence, nanophotonics encompasses many new and useful phenomena not found in macroscopic systems. In this course, we will explore the physics of light-matter coupling before using it as a guide to engineer new optical material properties via nanofabrication, with applications in computing, telecommunications, biomedical sensing, solar energy harvesting, robotics and more. Key topics covered in the course include Mie resonant dielectric antennas, plasmonic antennas, negative and zero refractive index metamaterials, chiral metamaterials, metasurface lenses and holograms, nonlinear and time dependent metasurfaces, Bragg mirrors, 3D photonic crystals, photonic crystal slab waveguides and cavities, guided mode resonators, photonic crystal lasers.
Credit 3 units.

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 ab in cavities. If 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 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 Stochastic 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: BME T, TU

E35 ESE 545 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.
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 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 551 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, memory hierarchies (cache and main memories, virtual memory), pipelining, instruction scheduling, and parallel systems. The course emphasizes understanding the performance implications of design choices, using architecture modeling and evaluation using simulation techniques. Prerequisites: CSE 361S and CSE 260M. Same as E81 CSE 560M
Credit 3 units. EN: BME T, 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. Prerequisite: E35 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: 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 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: BME T, 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 cover the protocol 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 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. 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

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.
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 broadbeam responses, radiative transfer equation, diffusion theory and applications, sensing of optical properties and spectroscopy, and photoacoustic imaging principles and applications. Prerequisite: Familiarity with Differential equations and partial 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. Further, concepts from generalized functions, Fourier analysis, and radon transform will 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 where stochastic models for objects and images will be introduced. Familiarity with Engineering-level mathematics, Calculus, Linear algebra, an introduction to Fourier analysis is expected. 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: BME T, 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. EN: TU

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.

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.