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 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.

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**Faculty**

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

**Endowed Professors**

Arye Nehorai ([https://engineering.wustl.edu/Profiles/Pages/Arye-Nehorai.aspx](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](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](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](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

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

Neal Patwari (https://ese.wustl.edu/faculty/Pages/faculty.aspx?bio=189)
Professor
PhD, University of Michigan
Intersection of statistical signal processing and wireless networking for improving wireless sensor networking and radiofrequency sensing

Heinz Schaeftlter (https://engineering.wustl.edu/Profiles/Pages/Heinz-Schaettler.aspx)
PhD, Rutgers University
Optimal control, nonlinear systems, mathematical models in biomedicine

Associate Professors
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

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

Assistant Professors
Ulubek 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

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

Senior Professors
Paul S. Min (https://ese.wustl.edu/faculty/Pages/Paul-Min.aspx)
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

William F. Pickard (https://ese.wustl.edu/faculty/Pages/William-Pickard.aspx)
PhD, Harvard University
Biological transport, electrobioology, energy engineering

Daniel L. Rode (https://ese.wustl.edu/faculty/Pages/Daniel-Rode.aspx)
PhD, Case Western Reserve University
Optoelectronics and fiber optics, semiconductor materials, light-emitting diodes and lasers, semiconductor processing, electronics

Ervin Y. Rodin (https://ese.wustl.edu/faculty/Pages/Ervin-Rodin.aspx)
PhD, University of Texas at Austin
Optimization, differential games, artificial intelligence, mathematical modeling

Barbara A. Shrauner (https://ese.wustl.edu/faculty/Pages/Barbara-Shrauner.aspx)
PhD, Harvard University (Radcliffe)
Plasma processing, semiconductor transport, symmetries of nonlinear differential equations

Donald L. Snyder (https://ese.wustl.edu/faculty/Pages/Donald-Snyder.aspx)
PhD, Massachusetts Institute of Technology
Communication theory, random process theory, signal processing, biomedical engineering, image processing, radar
Barry E. Spielman (https://ese.wustl.edu/faculty/Pages/Barry-Spielman.aspx)
PhD, Syracuse University
High-frequency/high-speed devices, radiofrequency and microwave integrated circuits, computational electromagnetics

Tzyh Jong Tarn (https://ese.wustl.edu/faculty/Pages/TJ-Tarn.aspx)
DSc, Washington University
Quantum mechanical systems, bilinear and nonlinear systems, robotics and automation, life science automation

Professors of Practice

Dedric Carter (https://ese.wustl.edu/faculty/Pages/faculty.aspx?bio=149)
PhD, Nova Southeastern University
MBA, MIT Sloan School of Management

Dennis Mell (https://ese.wustl.edu/faculty/Pages/faculty.aspx?bio=150)
MS, University of Missouri-Rolla
Industrial automation, robotics and mechatronics, product design and development with design-for-manufacturability emphasis, prototyping, manufacturing

Ed Richter (https://ese.wustl.edu/faculty/Pages/faculty.aspx?bio=151)
MS, Washington University
Signal processing applications implemented on a variety of platforms, including ASIC, FPGA, DSP, microcontroller and desktop computers

Jason Trobaugh (https://ese.wustl.edu/faculty/Pages/faculty.aspx?bio=152)
DSc, Washington University
Ultrasound imaging, diffuse optical tomography, image-guided therapy, and ultrasonic temperature imaging

Senior Lecturer

Martha Hasting (https://ese.wustl.edu/faculty/Pages/faculty.aspx?bio=156)
PhD, Saint Louis University
Mathematics education

James Feher (https://ese.wustl.edu/faculty/Pages/faculty.aspx?bio=155)
PhD, Missouri University of Science and Technology

Lecturers

Randall Brown (https://ese.wustl.edu/faculty/Pages/faculty.aspx?bio=154)
PhD, Washington University

Randall Hoven (https://ese.wustl.edu/faculty/Pages/faculty.aspx?bio=157)
MS, Johns Hopkins University

Vladimir Kurenok (https://ese.wustl.edu/faculty/Pages/faculty.aspx?bio=158)
PhD, Belarus State University (Minsk, Belarus)
Probability and stochastic processes, stochastic ordinary and partial differential equations, financial mathematics

Tsitsi Madziwa-Nussinov (https://ese.wustl.edu/faculty/Pages/faculty.aspx?bio=159)
PhD, University of California, Los Angeles

Jinsong Zhang (https://ese.wustl.edu/faculty/Pages/faculty.aspx?bio=160)
PhD, University of Miami
Modeling and performance analysis of wireless sensor networks, multi-source information fusion, ambiguous and incomplete information processing

Professors Emeriti

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

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

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

- Doctoral Degrees (http://bulletin.wustl.edu/grad/engineering/electrical/doctoral-degrees)
- Master of Science in Electrical Engineering (MSEE) (http://bulletin.wustl.edu/grad/engineering/electrical/ms-electrical)
• Master of Science in Systems Science & Mathematics (MSSSM) (http://bulletin.wustl.edu/grad/engineering/electrical/ms-systems-science-mathematics)
• Master of Science 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/mceng-control)
• Master of Engineering in Robotics (MEngR) (http://bulletin.wustl.edu/grad/engineering/electrical/mengr-robotics)
• Certificate in Imaging Science & Engineering (IS&E) (http://bulletin.wustl.edu/grad/engineering/electrical/certificate-imaging-science)

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

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

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. Prerequisites: ESE 520 (Probability and Stochastic Processes), Math 429 (Linear Algebra) or equivalent.
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: 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 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: 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, abd atoms 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 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. Prerequisites: 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. Prerequisite: ESE
551, ESE 552.
Credit 3 units. EN: BME T, TU

E35 ESE 545 Stochastic Control
Introduction to the theory of stochastic differential equations
based on Wiener processes and Poisson counters, and an
introduction to random fields. The formulation and solution of
problems in nonlinear estimation theory. The Kalman-Bucy
filter and nonlinear analogues. Identification theory. Adaptive
systems. Applications. Prerequisites: ESE 520 and ESE 551.
Credit 3 units. EN: BME T, 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. 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, Barbatal'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 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.

E35 ESE 552 Linear Dynamic Systems II
Least squares optimization problems. Riccati equation, terminal
regulator and steady-state regulator. Introduction to filtering
and stochastic control. Advanced theory of linear dynamic
systems. Geometric approach to the structural synthesis of linear
multivariable control systems. Disturbance decoupling, system
invertibility and decoupling, extended decoupling and the internal
model principle. Prerequisite: ESE 551.
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
Differentiable manifolds, vector fields, distributions on a
manifold, Frobenius’ theorem, Lie algebras. Controllability,
observability of nonlinear systems, examined from the viewpoint
of differential geometry. Transformation to normal forms. Exact
linearization via feedback. Zero dynamics and related properties.
Noninteracting control and disturbance decoupling. Controlled
invariant distributions. Noninteracting control with internal
stability. Prerequisites: ESE 553 and ESE 551.
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.

E35 ESE 559 Special Topics in Systems and Control:
Control of High-Dimensional Complex Systems
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, and 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 the state-of-
the-art research in the field, and ultimately apply their knowledge
to conduct a final project. Prerequisite: Linear algebra (Math
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 ESE 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. 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: 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 tradeoffs between performance, power consumption, energy efficiency, reliability, and programmability. Students will gain insight into the early stage of the SoC design process by performing the tasks of developing functional specification, partition and map functions onto hardware and/or software then 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: 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, 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 queuing theory, analysis of single queues, queuing 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 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: BME T, 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 the opportunity to seek the sparsest possible representation or the one with the fewest nonzeros. 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; coding 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 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