ELECTRICAL & SYSTEMS ENGINEERING (ESE)

ESE 099 Undergraduate Research and/or Independent Study
An opportunity for the student to become closely associated with a professor in (1) a research effort to develop research skills and technique and/or (2) to develop a program of independent in-depth study in a subject area in which the professor and student have a common interest. The challenge of the task undertaken must be consistent with the student's academic level. To register for this course, the student and professor jointly submit a detailed proposal to the undergraduate curriculum chairman no later than the end of the first week of the term.
One-term course offered either term
Activity: Independent Study
1.0 Course Unit
Notes: A maximum of 2 c.u. of ESE 099 may be applied toward the B.A.S. or B.S.E. degree requirements

ESE 111 Atoms, Bits, Circuits and Systems
Introduction to the principles underlying electrical and systems engineering. Concepts used in designing circuits, processing signals on analog and digital devices, implementing computation on embedded systems, analyzing communication networks, and understanding complex systems will be discussed in lectures and illustrated in the laboratory. This course provides an overview of the challenges and tools that Electrical Engineers and Systems Engineers address and some of the necessary foundations for students interested in more advanced courses in ESE. Prerequisite: FOR FRESHMAN ONLY
Course usually offered in fall term
Activity: Lecture
1.0 Course Unit
Notes: Freshmen only

ESE 112 Engineering Electromagnetics
This course covers basic topics in engineering electromagnetics, namely, electric charge, electric field, electric energy, conductors, insulators, dielectric materials, capacitors, electric current, magnetic field, inductors, Faraday’s law of induction, alternating current (AC), impedance, Maxwell's equations, electromagnetic and optical wave propagation, with emphasis on engineering issues. Relevant engineering topics are emphasized in our lectures in order to prepare students for other courses in ESE that rely on the contents on this course. Several laboratory experiments accompany the course to provide hands-on experience on some of the topics in the lecture and prepare students for the capstone project.
Course usually offered in spring term
Activity: Lecture
1.5 Course Unit

ESE 150 Digital Audio Basics
Primer on digital audio. Overview of signal processing, sampling, compression, human psychoacoustics, MP3, intellectual property, hardware and software platform components, and networking (i.e., the basic technical underpinnings of modern MP3 players and cell phones). Prior programming experience (CIS 110, ENGR 105) is sufficient for enrolling in this course.
Taught by: Andre DeHon
Course usually offered in spring term
Activity: Lecture
1.0 Course Unit
Notes: Freshmen only

ESE 190 Silicon Garage: Introduction to Open Source Hardware and Software Platforms
Project-centric learning course for non-ESE majors on microprocessor control of physical systems using open-source hardware and software platforms. Students will work in teams to develop software controlled systems based on the Arduino and Raspberry-Pi that interface with the real world (sensors, actuators, motors) and each other (networking).
Prerequisite: High School Physics and Math
Course usually offered in spring term
Activity: Lecture
0.5 Course Units

ESE 204 Decision Models
This first course in decision models will introduce students to quantitative models for decision making, using optimization and monte-carlo simulation. Examples will be drawn from manufacturing, finance, logistics and supply chain management. Students will use EXCEL and @Risk to build and analyze models.
Course usually offered in fall term
Prerequisite: MATH 104
Activity: Lecture
1.0 Course Unit

ESE 210 Introduction to Dynamic Systems
This first course in systems modelling covers linear and nonlinear systems in both continuous and discrete time. Topics covered include linearization and stability analysis, elementary bifurcations, and an introduction to chaotic dynamics. Extensive applications to mechanical, electrical, biological, social, and economic/financial systems are included. The course will use both analytical and numerical/symbolic tools.
Course usually offered in fall term
Corequisite: MATH 240
Activity: Lecture
1.0 Course Unit

ESE 215 Electrical Circuits and Systems
This course gives an introduction of modern electric and electronic circuits and systems. Designing, building and experimenting with electrical and electronic circuits are challenging and fun. It starts with basic electric circuit analysis techniques of linear circuits. Today mathematical analysis is used to gain insight that supports design; and more detailed and accurate representations of circuit performance are obtained using computer simulation. It continues with 1st order and 2nd order circuits in both the time and frequency domains. It discusses the frequency behavior of circuits and the use of transfer functions. It continues with introduction of non-linear elements such as diodes and MOSFET (MOS) transistors. Applications include analog and digital circuits, such as single stage amplifiers and simple logic gates. A weekly lab accompanies the course where concepts discussed in class will be illustrated by hands-on projects; students will be exposed to state-of-the-art test equipment and software tools (LabView, Spice).
Course usually offered in fall term
Prerequisites: PHYS 150, 151
Corequisite: MATH 240
Activity: Lecture
1.5 Course Unit
ESE 218 Electronic, Photonic, and Electromechanical Devices
This first course in electronic, photonic and electromechanical devices introduces students to the design, physics and operation of physical devices found in today's applications. The course describes semiconductor electronic and optoelectronic devices, including light-emitting diodes, photodetectors, photovoltaics, transistors and memory; optical and electromagnetic devices, such as waveguides, fibers, transmission lines, antennas, gratings, and imaging devices; and electromechanical actuators, sensors, transducers, machines and systems.
Course usually offered in fall term
Prerequisites: PHYS 150, 151
Corequisite: MATH 240
Activity: Lecture
1.5 Course Unit

ESE 224 Signal and Information Processing
Introduction to signal and information processing (SIP). In SIP we discern patterns in data and extract the patterns from noise. Foundations of deterministic SIP in the form of frequency domain analysis, sampling, and linear filtering. Random signals and the modifications of deterministic tools that are necessary to deal with them. Multidimensional SIP where the goal is to analyze signals that are indexed by more than one parameter. Includes a hands-on lab component that implements SIP as standalone applications on modern mobile platforms.
Course usually offered in spring term
Prerequisite: MATH 104
Corequisite: MATH 240
Activity: Lecture
1.5 Course Unit

ESE 290 Introduction to Electrical and Systems Engineering Research Methodology
Introduction to the nature and process of engineering research as represented by ongoing ESE faculty (and collaborating colleagues’ and industrial partners’) research projects. Joint class exercises in how to pursue effective background technical reading, pitch a proposal, and aim for the discovery of new human knowledge to complement the individually mentored topic specific project work.
Course usually offered in spring term
Prerequisites: MATH 240, 150, ESE 215 218 or ESE 204, 210 or ESE 215 and CIS 240
Corequisite: ESE 291
Activity: Lecture
0.5 Course Units

ESE 291 Introduction to Electrical and Systems Engineering Research and Design
Students contract with a faculty mentor to conduct scaffolded original research in a topic of mutual interest. Prepare project report on research findings.
Course usually offered in spring term
Corequisite: ESE 290
Activity: Laboratory
1.0 Course Unit

ESE 292 Introduction to Electromechanical Prototyping
This is a project-centric course for ESE majors to engage in circuit layout and prototype design skills. Students will work in teams to develop printed circuit boards using industry standard tools like Altium and learn mechanical prototyping skills using Solidworks. Emphasis will be on developing sound printed circuit board layout practices using circuitry knowledge that they acquire in ESE 215 and ESE 370. A module on using Cypress PSoC will introduce students to recent developments in analog/digital co-design.
Course usually offered in spring term
Activity: Lecture
0.5 Course Units

ESE 296 Study Abroad
Activity: Lecture
1.0 Course Unit

ESE 301 Engineering Probability
This course introduces students to the mathematical foundations of the theory of probability and its rich applications. The course begins with an exploration of combinatorial probabilities in the classical setting of games of chance, proceeds to the development of an axiomatic, fully mathematical theory of probability, and concludes with the discovery of the remarkable limit laws and the eminence grise of the classical theory, the central limit theorem. The topics covered include: discrete and continuous probability spaces, distributions, mass functions, densities; conditional probability; independence; the Bernoulli schema: the binomial, Poisson, and waiting time distributions; uniform, exponential, normal, and related densities; expectation, variance, moments; conditional expectation; generating functions, characteristic functions; inequalities, tail bounds, and limit laws. But a bald listing of topics does not do justice to the subject: the material is presented in its lush and glorious historical context, the mathematical theory buttressed and made vivid by rich and beautiful applications drawn from the world around us. The student will see surprises in election-day counting of ballots, a historical wager the sun will rise tomorrow, the folly of gambling, the sad news about lethal genes, the curiously persistent illusion of the hot hand in sports, the unreasonable efficacy of polls and its implications to medical testing, and a host of other beguiling settings.
Course usually offered in spring term
Prerequisite: MATH 114
Activity: Lecture
1.0 Course Unit
**ESE 303 Stochastic Systems Analysis and Simulation**

Stochastic systems analysis and simulation (ESE 303) is a class that explores stochastic systems which we could loosely define as anything random that changes in time. Stochastic systems are at the core of a number of disciplines in engineering, for example communication systems and machine learning. They also find application elsewhere, including social systems, markets, molecular biology and epidemiology. The goal of the class is to learn how to model, analyze and simulate stochastic systems. With respect to analysis we distinguish between what we could call theoretical and experimental analysis. By theoretical analysis we refer to a set of tools which let us discover and understand properties of the system. These analysis can only take us so far and is usually complemented with numerical analysis of experimental outcomes. Although we use the word experiment more often than not we simulate the stochastic system in a computer and analyze the outcomes of these virtual experiments. Prerequisite: One computer language The class’s material is divided in four blocks respectively dealing with Markov chains, continuous time Markov chains, Gaussian processes and stationary processes. Emphasis is placed in the development of toolboxes to analyze these different classes of processes and on describing their applications to complex stochastic systems in different disciplines. Particular examples include: (i) the problem of ranking web pages by a search engine; (ii) the study of reputation and trust in social networks; (iii) modeling and analysis of communication networks; (iv) the use of queues in the modeling of transportation networks; (v) stochastic modeling and simulation of biochemical reactions and gene networks; (vi) arbitrage, pricing of stocks, and pricing of options through Black-Scholes formula; and (vii) linear filtering of stochastic processes to separate signals of interest from background noise. For more information visit the class’s web page at http://alliance.seas.upenn.edu/~ese303/ wiki/.

Course usually offered in fall term  
Prerequisite: ESE 301  
Activity: Lecture  
1.0 Course Unit

**ESE 305 Foundations of Data Science**

Introduction to a broad range of tools to analyze large volumes of data in order to transform them into actionable decisions. Using case studies and hands-on exercises, the student will have the opportunity to practice and increase their data analysis skills.

Course usually offered in fall term  
Prerequisites: EAS 205 or MATH 312 and CIS 120 and ESE 301  
Activity: Lecture  
1.0 Course Unit

**ESE 310 Electric and Magnetic Fields I**

This course examines concepts of electromagnetism, vector analysis, electrostatic fields, Coulomb’s Law, Gauss’s Law, magnetostatic fields, Biot-Savart Law, Ampere’s Law, electromagnetic induction, Faraday’s Law, transformers, Maxwell equations and time-varying fields, wave equations, wave propagation, dipole antenna, polarization, energy flow, and applications.

Course not offered every year  
Prerequisite: PHYS 151 AND MATH 114  
Activity: Lecture  
1.0 Course Unit

**ESE 319 Fundamentals of Solid-State Circuits**

Analysis and design of basic active circuits involving semiconductor devices including diodes and bipolar transistors. Single stage, differential, multi-stage, and operational amplifiers will be discussed including their high frequency response. Wave shaping circuits, filters, feedback, stability, and power amplifiers will also be covered. A weekly three-hour laboratory will illustrate concepts and circuits discussed in the class.

Course usually offered in spring term  
Prerequisite: ESE 215  
Activity: Lecture  
1.5 Course Unit

**ESE 325 Fourier Analysis and Applications in Engineering, Mathematics, and the Sciences**

This course focuses on the mathematics behind Fourier theory and a wide variety of its application in diverse problems in mathematics, engineering, and the sciences. The course is very mathematical in content and students signing up for it should have junior or senior standing. The topics covered are chosen from: functions and signals; systems of differential equations; superposition, memory, and non-linearity; resonance, eigenfunctions; the Fourier series and transform, spectra; convergence theorems; inner product spaces; mean-square approximation; interpolation and prediction, sampling; random processes, stationarity; wavelets, Brownian motion; stability and control, Laplace transforms. Prerequisite: Junior or Senior standing

The applications of the mathematical theory that will be presented vary from year to year but a representative sample include: polynomial approximation, Weierstrass’s theorem; efficient computation via Monte Carlo; linear and non-linear oscillators; the isoperimetric problem; the heat equation, underwater communication; the wave equation, tides; testing for randomness, fraud; nowhere differentiable continuous functions; does Brownian motion exist?; error-correction; phase conjugate optics and four-wave mixing; cryptography and secure communications; how fast can we compute?; X-ray crystallography; cosmology; and what the diffusion equation has to say about mathematical finance and arbitrage opportunities.

Course usually offered in fall term  
Prerequisite: MATH 240  
Activity: Lecture  
1.0 Course Unit

**ESE 330 Principles of Optics and Photonics**

This course introduces the fundamental principles of optics, photonics, and antennas alongside a range of applications. Specific topics include: Maxwell’s equations and the wave equation; light propagation and interaction with materials; geometric/ray optics and polarization; wave optics, diffraction and gratings; waveguides and fiber optics; optical cavities; lasers and light sources; antennas and applications to wireless communication. Prerequisite: Permission of Instructor

Prerequisites: ESE 215, 218  
Activity: Lecture  
1.0 Course Unit
ESE 336 Nanofabrication of Electrical Devices
This course is an intermediate undergraduate course in the understanding, fabrication, and characterization of electrical, optical, electromagnetic, and/or electromechanical nanodevices; i.e., micro- and nanoscale devices which have significant relevance to electrical engineering. Example devices of interest include transistors, microelectromechanical systems (MEMS), and optical and optoelectronic devices (including photovoltaic devices). Weekly laboratory sessions will enable the fabrication and characterization of a subset of electrical nanodevices. Students will learn basic physics and modeling of electrical nanodevices as well as acquire hands-on skill in their fabrication and characterization. Prerequisite: If course requirements not met, permission of instructor required.
Course usually offered in spring term
Prerequisite: ESE 218
Activity: Lecture
1.5 Course Unit

ESE 350 Embedded Systems/Microcontroller Laboratory
An introduction to interfacing real-world sensors and actuators to embedded microprocessor systems. Concepts needed for building electronic systems for real-time operation and user interaction, such as digital input/outputs, interrupt service routines, serial communications, and analog-to-digital conversion will be covered. The course will conclude with a final project where student-designed projects are featured in presentations and demonstrations. Prerequisite: Prior programming experience in any language
Taught by: Kim Luong
Course usually offered in spring term
Activity: Lecture
1.5 Course Unit

ESE 370 Circuit-Level Modeling, Design, and Optimization for Digital Systems
Circuit-level design and modeling of gates, storage, and interconnect. Emphasis on understanding physical aspects which drive energy, delay, area, and noise in digital circuits. Impact of physical effects on design and achievable performance.
Course usually offered in fall term
Prerequisites: ESE 150, 215
Activity: Lecture
1.0 Course Unit

ESE 400 Engineering Economics
This course investigates methods of economic analysis for decision making among alternative courses of action in engineering applications. Topics include: cost-driven design economics, break-even analysis, money-time relationships, rates of return, cost estimation, depreciation and taxes, foreign exchange rates, life cycle analysis, benefit-cost ratios, risk analysis, capital financing and allocation, and financial statement analysis. Case studies apply these topics to actual engineering problems. Prerequisite: Knowledge of Differential Calculus
Course usually offered in fall term
Also Offered As: ESE 540
Activity: Lecture
1.0 Course Unit

ESE 401 Complex Networks
The course covers the methodological foundations of network formation and utilization. It introduces various mathematical models for random and strategic, static and dynamic formation of networks. The models for random static formation span, Erdos Renyi Graphs and Power law topologies. Threshold properties underlying these formations will be rigorously proved. The dynamic formations will introduce mean field based deterministic models for network evolution. Techniques for approximately analyzing various key network features such as component sizes will be introduced. These analyses will culminate in tools for approximate analysis of efficacy of various immunization strategies considering epidemic disease spread over networks. A solid background in undergraduate probability is required (e.g. ESE 301, STAT 430, ENM 321, CIS 261 or equivalent).
Taught by: Saswati Sarkar
Course usually offered in spring term
Also Offered As: ESE 501
Activity: Lecture
1.0 Course Unit

ESE 402 Statistics for Data Science
The course covers the methodological foundations of data science, emphasizing basic concepts in statistics and learning theory, but also modern methodologies. Learning of distributions and their parameters. Testing of multiple hypotheses. Linear and nonlinear regression and prediction. Classification. Uncertainty quantification. Model validation. Clustering. Dimensionality reduction. Probably approximately correct (PAC) learning. Such theoretical concepts are further complemented by exemplary applications, case studies (datasets), and programming exercises (in Python) drawn from electrical engineering, computer science, the life sciences, finance, and social networks.
Course usually offered in fall term
Also Offered As: ESE 542
Prerequisites: ESE 301 and CIS 110, 120
Activity: Lecture
1.0 Course Unit

ESE 407 Introduction to Networks and Protocols
This is an introductory course on packet networks and associated protocols, with a particular emphasis on IP-based networks such as the Internet. The course introduces design and implementation choices that underlie the development of modern networks, and emphasizes basic analytical understanding of the concepts. Topics are covered in a mostly "top down" approach starting with web HTTP protocol followed by transport layer protocols such as TCP and UDP. Congestion control of TCP is extensively covered. Network layer solutions, including IP addressing and routing are covered next, before exploring link layer solutions including multiple access strategies, local area networks (Ethernet and 802.11). The objectives of the course include basic understanding of the network protocol stack and hands-on experience analyzing protocol behavior using wireshark.
Taught by: Joy Wang
Course usually offered in fall term
Also Offered As: ESE 507
Prerequisite: ESE 301
Activity: Lecture
1.0 Course Unit
Notes: Course open to Seniors in SEAS and Wharton
### ESE 419 Analog Integrated Circuits
Design of analog circuits and subsystems using primarily MOS technologies at the transistor and higher levels. Transistor level design of building block circuits such as op amps, comparators, sample and hold circuits, voltage and current references, capacitors and resistor and class AB output stages. The Cadence Design System will be used to capture schematics and run simulations using Spectre for some homework problems and for the course project. Topics of stability, noise, device matching through good layout practice will also be covered. Students who take ESE419 will not be able to take ESE572 later. More will be expected of ESE572 students in the design project. Prerequisite: If course requirement not met, permission of instructor required. Course usually offered in fall term Also Offered As: ESE 572 Prerequisite: ESE 319 Activity: Lecture 1.0 Course Unit

### ESE 420 Agent-Based Modeling and Simulation
Agents are a new technique for trying to model, simulate, and understand systems that are ill-structured and whose mathematics is initially unknown and possibly unknowable. This approach allows the analyst to assemble models of agents and components where micro-decision rules may be understood; to bring the agents and components together as a system where macro-behavior then emerges; and to use that to empirically probe and improve understanding of the whole, the interrelations of the components, and synergies. This approach helps one explore parametrics, causality, and what-if's about socio-technical systems (technologies that must support people, groups, crowds, organizations, and societies). It is applicable when trying to model and understand human behavior - consumers, investors, passengers, plant operators, patients, voters, political leaders, terrorists, and so on. This course will allow students to investigate and compare increasingly complex agent based paradigms along three lines - math foundations, heuristic algorithms/knowledge representations, and empirical science. The student will gain a toolbox and methodology for attempting to represent and study complex socio-technical systems. Course usually offered in fall term Activity: Lecture 1.0 Course Unit

### ESE 421 Control For Autonomous Robots
This course introduces the hardware, software and control technology used in autonomous ground vehicles, commonly called "self-driving cars." The weekly laboratory sessions focus on development of a small-scale autonomous car, incrementally enhancing the sensors, software, and control algorithms to culminate in a demonstration in a realistic outdoor operating environment. Students will learn basic physics and modeling; controls design and analysis in Matlab and Simulink; software implementation in C and Python; sensor systems and filtering methods for IMUs, GPS, and computer vision systems; and path planning from fixed map data. Prerequisite: If course requirement not met, permission of instructor required. Course usually offered in fall term Also Offered As: MEAM 421 Prerequisite: (CIS 110 OR CIS 120 OR ENGR 105) AND (ESE 210 OR ESE 215 OR MEAM 211) Activity: Lecture 1.5 Course Unit

### ESE 423 Quantum Engineering
Quantum engineering - the design, fabrication, and control of quantum coherent devices - has emerged as a multidisciplinary field spanning physics, electrical engineering, materials science, chemistry, and biology, with the potential for transformational advances in computation, secure communication, and nanoscale sensing. This course surveys the state of the art in quantum hardware, beginning with an overview of the physical implementation requirements for a quantum computer and proceeding to a synopsis of the leading contenders for quantum building blocks, including spins in semiconductors, superconducting circuits, photons, and atoms. The course combines background material on the fundamental physics and engineering principles required to build and control these devices with readings drawn from the current literature, including promising architectures for scaling physical qubits into larger devices and secure communication networks, and for nanoscale sensing applications impacting biology, chemistry, and materials. Prerequisite: If course requirement not met, permission of instructor required. Course usually offered in spring term Also Offered As: ESE 523 Prerequisite: PHYS 411 Activity: Lecture 1.0 Course Unit

### ESE 444 Project Management
The course emphasizes a systems engineering approach to project management including the cycle costing and analysis, project scheduling, project organization and control, contract management, project monitoring and negotiations. In addition, the course will also examine management issues in large infrastructure projects like non-recourse or limited recourse project financing. Examples from the logistics planning process and global software project management will be used to highlight the course topics. Two terms. student may enter either term. Also Offered As: ESE 544 Prerequisite: ESE 304 Activity: Lecture 1.0 Course Unit

### ESE 450 Senior Design Project I - EE and SSE
This is the first of a two-semester sequence in electrical and systems engineering senior design. Student work will focus on project/team definition, systems analysis, identification alternative design strategies and determination (experimental or by simulation) or specifications necessary for a detailed design. Project definition is focused on defining a product prototype that provides specific value to a least one identified user group. Students will receive guidance on preparing professional written and oral presentations. Each project team will submit a project proposal and two written project reports that include coherent technical presentations, block diagrams and other illustrations appropriate to the project. Each student will deliver two formal Powerpoint presentations to an audience comprised of peers, instructors and project advisors. During the semester there will be periodic individual/team project reviews. Prerequisite: Senior Standing or permission of the instructor Course usually offered in fall term Activity: Lecture 1.0 Course Unit
ESE 451 Senior Design Project II - EE and SSE
This is the second of a two term sequence in electrical and systems engineering senior design. Student work will focus on completing the product prototype design undertaken in ESE 450 and successfully implementing the said product prototype. Success will be verified using experimental and/or simulation methods appropriate to the project that test the degree to which the project objectives are achieved. Each project team will prepare a poster to support a final project presentation and demonstration to peers, faculty and external judges. The course will conclude with the submission of a final project written team report. During the semester there will be periodic project reviews with individual teams.
Course usually offered in spring term
Prerequisite: ESE 450
Activity: Lecture
1.0 Course Unit

ESE 460 The Principles and Practice of Microfabrication Technology
A laboratory-based course on fabricating microelectronic and micromechanical devices using photolithographic processing and related fabrication technologies. Lectures discuss: clean room procedures; microelectronic and microstructural materials; photolithography; diffusion, oxidation; materials deposition; etching and plasma processes. Basic laboratory processes are covered for the first two thirds of the course with students completing structures appropriate to their major in the final third. Students registering for ESE 574 will be expected to do extra work (including term paper and additional project).
Course not offered every year
Also Offered As: ESE 574, MEAM 564
Prerequisites: ESE 218, MSE 321, MEAM 333, CBE 351, PHYS 250
Activity: Lecture
1.0 Course Unit

ESE 500 Linear Systems Theory
This graduate-level course focuses on continuous and discrete n-dimensional linear systems with m inputs and p outputs in a time domain based on linear operators. The course covers general discussions of linear systems such as, linearization of non-linear systems, existence and uniqueness of state-equation solutions, transition matrices and their properties, methods for computing functions of matrices and transition matrices and state-variable changes. It also includes z-transform and Laplace transform methods for time-invariant systems and Floquet decomposition methods for periodic systems. The course then moves to stability analysis, including: uniform stability, uniform exponential stability, asymptotic stability, uniform asymptotic stability, Lyapunov transformations, Lyapunov stability criteria, eigenvalues conditions and input-output stability analysis. Applications involving the topics of controllability, observability, realizability, minimal realization, controller and observer forms, linear feedback, and state feedback stabilization are included, as time permits. Open to graduates and undergraduates who have taken undergraduate courses in linear algebra and differential equations.
Course usually offered in fall term
Activity: Lecture
1.0 Course Unit

ESE 501 Networking - Theory and Fundamentals
Networks constitute an important component of modern technology and society. Networks have traditionally dominated communication technology in form of communication networks, distribution of energy in form of power grid networks, and have more recently emerged as a tool for social connectivity in form of social networks. In this course, we will study mathematical techniques that are key to the design and analysis of different kinds of networks. First, we will investigate techniques for modeling evolution of networks. Specifically, we will consider random graphs (all or none connectivity, size of components, diameters under random connectivity), small world problem, network formation and the role of topology in the evolution of networks. Next, we will investigate different kinds of stochastic processes that model the flow of information in networks. Specifically, we will develop the theory of markov processes, renewal processes, and basic queueing, diffusion models, epidemics and rumor spreading in networks.
Course usually offered in spring term
Also Offered As: ESE 401
Prerequisite: ESE 530
Activity: Lecture
1.0 Course Unit

ESE 503 Simulation Modeling and Analysis
This course provides a study of discrete-event systems simulation in the areas of queuing, inventory and reliability systems as well as Markov Chain, Random-Walks and Monte-Carlo systems. The course examines many probability distributions used in simulation studies as well as the Poisson process. Fundamental to most simulation studies is the ability to generate reliable random numbers and so the course investigates the basic properties of random numbers and techniques used for the generation and testing of pseudo-random numbers. Random numbers are then used to generate other random variable using the methods of inverse-transform, convolution, composition and acceptance/rejection. Finally, since most inputs to simulation are probabilistic instead of deterministic in nature, the course examines some techniques used for identifying the probabilistic nature of input data. These include identifying distributional families with sample data, using maximum-likelihood methods for parameter estimating within a given family and testing the final choice of distribution using chi-squared goodness-of-fit.
Course usually offered in spring term
Activity: Lecture
1.0 Course Unit

ESE 504 Intro to Linear, Nonlinear and Integer Optimization
Introduction to mathematical optimization for graduate students who would like to be intelligent and sophisticated users of mathematical programming but do not necessarily plan to specialize in this area. Linear, integer and nonlinear programming are covered, including the fundamentals of each topic together with a sense of the state-of-the-art and expected directions of future progress. Homework and projects emphasize modeling and solution analysis, and introduce the students to a large variety of application areas.
Course usually offered in fall term
Also Offered As: OIDD 910
Activity: Lecture
1.0 Course Unit
ESE 505 Feedback Control Design and Analysis
Basic methods for analysis and design of feedback control in systems. Applications to practical systems. Methods presented include time response analysis, frequency response analysis, root locus, Nyquist and Bode plots, and the state-space approach. Course usually offered in spring term
Also Offered As: MEAM 513
Prerequisite: MEAM 321 OR ESE 210
Activity: Lecture
1.0 Course Unit

ESE 506 Introduction to Optimization Theory
Introduction to mathematical optimization for graduate students who would like to be intelligent and sophisticated users of mathematical programming but do not necessarily plan to specialize in this area. Linear, integer and nonlinear programming are covered, including the fundamentals of each topic together with a sense of the state-of-the-art and expected directions of future progress. Homework and projects emphasize modeling and solution analysis, and introduce the students to a large variety of application areas.
Taught by: Michael Carchidi
Course usually offered in fall term
Activity: Lecture
1.0 Course Unit

ESE 507 Introduction to Networks and Protocols
This is an introductory course on packet networks and associated protocols, with a particular emphasis on IP-based networks such as the Internet. The course introduces design and implementation choices that underlie the development of modern networks, and emphasizes basic analytical understanding of the concepts. Topics are covered in a mostly "bottom-up" approach starting with a brief review of physical layer issues such as digital transmission, error correction and error recovery strategies. This is followed by a discussion of link layer aspects, including multiple access strategies, local area networks (Ethernet and 802.11 wireless LANs), and general store-and-forward packet switching. Network layer solutions, including IP addressing, naming, and routing are covered next, before exploring transport layer and congestion control protocols (UDP and TCP). Finally, basic approaches for quality-of-service and network security are examined. Specific applications and aspects of data compression and streaming may also be covered.
Course usually offered in fall term
Also Offered As: ESE 407
Activity: Lecture
1.0 Course Unit
Notes: Course open to Graduate Students in SEAS and Wharton

ESE 510 Electromagnetic and Optics
This course reviews electrostatics, magnetostatics, electric and magnetic materials, induction, Maxwell’s equations, potentials and boundary-value problems. Topics selected from the areas of wave propagation, wave guidance, antennas, and diffraction will be explored with the goal of equipping students to read current research literature in electromagnetics, microwaves, and optics.
Course usually offered in fall term
Activity: Lecture
1.0 Course Unit

ESE 512 Dynamical Systems for Engineering and Biological Applications
This midlevel course in nonlinear dynamics focuses on the analysis of low dimensional, continuous time models for describing and understanding complex behavior in physical, biological and engineered systems. We assume some background knowledge of ordinary differential equations, and develop at an engineering applications level the concepts and tools of qualitative dynamical systems theory with major focus on analysis and some on synthesis.
Course usually offered in fall term
Prerequisites: MATH 240, PHYS 150, ESE 210
Activity: Lecture
1.0 Course Unit

ESE 513 Prin of Quantum Tech
Course usually offered in fall term
Activity: Lecture
1.0 Course Unit

ESE 514 Graph Neural Networks
Graph Neural Networks (GNNs) are information processing architectures for signals supported on graphs. They have been developed and are presented in this course as generalizations of the convolutional neural networks (CNNs) that are used to process signals in time and space. The focus of this course is in large scale problems involving high dimensional signals. In these settings fully connected neural networks fail to scale. CNNs are the tool for enabling scalable learning for signals in time and space. GNNs are the tool for enabling scalable learning for signals supported on graphs.
Taught by: Alejandro Ribeiro
Course usually offered in fall term
Activity: Lecture
1.0 Course Unit

ESE 515 Internet of Things Sensors and Systems
The course is designed to introduce sensors and their networks and systems that are increasingly pervasive and form the physical device layer of the Internet of Things. Sensors transduce input signals into measured outputs within and between chemical, thermal, mechanical, optical, electrical, and magnetic domains. The course will describe the physical principles of operation, the characteristics, and the figures of merit of different sensors and their integration in networks and systems, highlighting common electronic interfaces that are used. The sensors and systems will be described as case studies to show how these devices are used to monitor and regulate processes in applications in agriculture, the environment, the home, manufacturing, health, transportation, and human activity. The course is structured with a combination of lectures, in-class and at-home labs, and research paper reading/in-class discussion.
Taught by: Cherie Kagan
Course usually offered in spring term
Prerequisite: ESE 218 AND MEAM 110 AND (MEAM 147 OR PHYS 150) AND (ESE 112 OR PHYS 151)
Activity: Lecture
1.0 Course Unit
ESE 516 IoT Edge Computing
This course was developed to bring lessons learned from the product design industry into the classroom - specifically focusing on Internet of Things (IoT) device development and deployment. To achieve the highest level of knowledge transfer, the course will incorporate device design theory with discussions of real-world product failures and successes - as well as a heavy hands-on component to build a device from end to end. Students will learn to use industry standard tools, such as Altium, Atmel Studio, and IBM Watson - allowing them the same level of power and customization at the disposable of startups and Fortune 500 companies alike. Prerequisite: If course requirement not met, permission of instructor required.
Course usually offered in spring term
Prerequisite: ESE 519
Activity: Lecture
1.0 Course Unit

ESE 519 Introduction to Embedded Systems
An embedded system is the product of a marriage between hardware and software. Embedded systems have grown to be ubiquitous in the modern world - from simple temperature controlled kettles to intricate smart watches with a plethora of functions squeezed into one small package to complex rovers for space exploration. This course introduces the theory and practice of developing embedded systems through exploration of modern microcontroller architectures and culminates in a final project where students have the opportunity to synthesize and apply their knowledge in a project of their own design. Previous programming experience (Preferably C); Some exposure to circuit/electronics; Undergraduates who have taken ESE350 are not permitted to take this course.
Taught by: Kim Luong
Course usually offered in fall term
Also Offered As: IPD 519
Activity: Lecture
1.0 Course Unit

ESE 521 The Physics of Solid State Energy Devices
An advanced undergraduate course or graduate level course on the fundamental physical principles underlying the operation of traditional semiconducting electronic and optoelectronic devices and extends these concepts to novel nanoscale electronic and optoelectronic devices. The course assumes an undergraduate level understanding of semiconductors physics, as found in ESE 218 or PHYS 240. The course builds on the physics of solid state semiconductor devices to develop the operation and application of semiconductors and their devices in energy conversion devices such as solar photovoltaics, thermophotovoltaics, and thermoelectrics, to supply energy. The course also considers the importance of the design of modern semiconductor transistor technology to operate at low-power in CMOS. Prerequisite: If course requirement not met, permission of instructor required.
Course usually offered in spring term
Prerequisite: ESE 218 OR PHYS 240
Activity: Lecture
1.0 Course Unit

ESE 523 Quantum Engineering
Quantum engineering - the design, fabrication, and control of quantum coherent devices - has emerged as a multidisciplinary field spanning physics, electrical engineering, materials science, chemistry, and biology, with the potential for transformational advances in computation, secure communication, and nanoscale sensing. This course surveys the state of the art in quantum hardware, beginning with an overview of the physical implementation requirements for a quantum computer and proceeding to a synopsis of the leading contenders for quantum building blocks, including spins in semiconductors, superconducting circuits, photons, and atoms. The course combines background material on the fundamental physics and engineering principles required to build and control these devices with readings drawn from the current literature, including promising architectures for scaling physical qubits into larger devices and secure communication networks, and for nanoscale sensing applications impacting biology, chemistry, and materials science.
Taught by: Lee Bassett
Course usually offered in spring term
Also Offered As: ESE 423
Prerequisite: ESE 513 AND (PHYS 411 OR PHYS 511)
Activity: Lecture
1.0 Course Unit

ESE 525 Nanoscale Science and Engineering
Overview of existing device and manufacturing technologies in microelectronics, optoelectronics, magnetic storage, Microsystems, and biotechnology. Overview of near- and long-term challenges facing those fields. Near- and long-term prospects of nanoscience and related technologies for the evolutionary sustention of current approaches, and for the development of revolutionary designs and applications. Prerequisite: If course requirement not met, permission of instructor required.
Course usually offered in fall term
Also Offered As: MSE 525
Prerequisite: ESE 218 OR PHYS 240 OR MSE 220
Activity: Lecture
1.0 Course Unit

ESE 527 Design of Smart Systems
Smart systems are materials, structures, devices and/or networks that seek to autonomously emulate human capabilities (sensing, nervous system, deliberating, acting) for adapting and continued functioning in potentially adverse conditions. Smart systems are a highly trans-disciplinary field that utilize microsystems technology with other disciplines like biology, information science, nanoscience, or cognitive science to control networks of components. Smart systems are causing a sea-change in hybrid cyber-physical-social systems leading to such breakthroughs as: the internet of Everything, smart cars, smart cities, the next industrial revolution, solutions to reduce global warming, and personalized e-healthcare, among many others. In this course students explore state-of-the-art smart system components, learn a design methodology to integrate the components, and apply the methodology to design and simulate a smart system prototype. The course will also cover life-long coping skills for human-centered design and for modeling the security, privacy and reliability hazards of the smart systems approach. Prerequisite: Junior or Senior standing, course or experience in a course with high level language
Course not offered every year
Activity: Lecture
1.0 Course Unit
ESE 528 Estimation and Detection Theory
Statistical decision making constitutes the core of multiple engineering systems like communication, networking, signal processing, control, market dynamics, biological systems, data processing, etc. We strive to introduce mathematical theories that formulate statistical decision and obtain decision making algorithms with application to one or more of the above domains. This course will be offered every other year.

One-term course offered either term
Prerequisite: ESE 530
Activity: Lecture
1.0 Course Unit

ESE 529 Introduction to Micro- and Nano-electromechanical Technologies

Taught by: Troy Olsson
Course usually offered in spring term
Also Offered As: MEAM 529
Activity: Lecture
1.0 Course Unit

ESE 530 Elements of Probability Theory
This rapidly moving course provides a rigorous development of fundamental ideas in probability theory and random processes. The course is suitable for students seeking a rigorous graduate level exposure to probabilistic ideas and principles with applications in diverse settings. The topics covered are drawn from: abstract probability spaces; combinatorial probabilities; conditional probability; Bayes’s rule and the theorem of total probability; independence; connections with the theory of numbers, Borel’s normal law; rare events, Poisson laws, and the Lovasz local lemma; arithmetic and lattice distributions arising from the Bernoulli scheme; limit laws and characterizations of the binomial and Poisson distributions; continuous distributions in one and more dimensions; the uniform, exponential, normal, and related distributions; random variables, distribution functions; orthogonal and stationary random processes; the Gaussian process, Brownian motion; random number generation and statistical tests of randomness; mathematical expectation and the Lebesgue theory; expectations of functions, moments, convolutions; operator methods and distributional convergence, the central limit theorem, selection principles; conditional expectation; tail inequalities, concentration convergence in probability and almost surely, the law of large numbers, the law of the iterated logarithm; Poisson approximation, Janson’s inequality, the Stein-Chen method; moment generating functions, renewal theory; characteristic functions. A solid foundation in undergraduate probability at the level of ESE 301 or STAT 430 at Penn. Students are expected to have a sound calculus background in the first two years of a typical undergraduate engineering curriculum. Undergraduates are warned that the course is very mathematical in nature with an emphasis on rigor; upperclassmen who wish to take the course will need to see the instructor for permission to register.

Course usually offered in fall term
Activity: Lecture
1.0 Course Unit

ESE 531 Digital Signal Processing
This course covers the fundamentals of discrete-time signals and systems and digital filters. Specific topics covered include: review of discrete-time signal and linear system representations in the time and frequency domain, and convolution; discrete-time Fourier transform (DTFT); Z-transforms; frequency response of linear discrete-time systems; sampling of continuous-time signals, analog to digital conversion, sampling-rate conversion; basic discrete-time filter structures and types; finite impulse response (FIR) and infinite impulse response (IIR) filters; design of FIR and IIR filters; discrete Fourier transform (DFT), the fast Fourier transform (FFT) algorithm and its applications in filtering and spectrum estimation.

Course usually offered in fall term
Prerequisites: ESE 224, 325
Activity: Lecture
1.0 Course Unit

ESE 532 System-on-a-Chip Architecture
Motivation, design, programming, optimization, and use of modern System-on-a-Chip (SoC) architectures. Hands-on coverage of the breadth of computer engineering within the context of SoC platforms from gates to application software, including on-chip memories and communication networks, I/O interfacing, RTL design of accelerators, processors, concurrency, firmware and OS/infrastructure software. Formulating parallel decompositions, hardware and software solutions, hardware/software tradeoffs, and hardware/software codesign. Attention to real-time requirements. Undergraduates: CIS 240, ESE 350; Graduate: Working knowledge of C.

Course usually offered in fall term
Activity: Lecture
1.0 Course Unit

ESE 533 Stochastic Processes
Stochastic modelling and analysis is key in understanding physical phenomena as well as designing new systems and quantifying various trade-offs and aspects of those designs. The course develops the foundations of stochastic processes and aims to provide engineering students with a mathematical, yet intuitive, toolbox to work with random processes. Topics covered include random walks, counting processes, renewal processes, Markov models and Markov decision processes, and martingales. Tools and techniques studied in this class are at the core of various fields ranging from engineering to social sciences and biology. Solid background in probability, preferably advanced probability, is required (e.g. ESE 501 or equivalent). Some calculus and linear algebra will be needed (e.g. MATH 104 and MATH 240)

Taught by: Shirin Saeedi Bidokhti
Course usually offered in fall term
Activity: Lecture
1.0 Course Unit

ESE 535 Electronic Design Automation
Analysis, and design of analysis mapping problems with emphasis on VLSI and computational realizations. Major themes include: formulating and abstracting problems, figures of merit (e.g. Energy, Delay, Throughput, Area, Mapping Time), representation, traditional decomposition of flow (logic optimization, covering, scheduling, retiming, assignment, partitioning, placement, routing), and techniques for solving problems (e.g. greedy, dynamic programming, search, (integer) linear programming, graph algorithms, randomization, satisfiability). Digital logic, Programming (need to be)

Course not offered every year
Activity: Lecture
1.0 Course Unit
ESE 536 Nanofabrication and Nanocharacterization
This course is intended for first year graduate students interested in the experimental practice of nanotechnology. In the context of a hands-on laboratory experience, students will gain familiarity with both top-down and bottom-up fabrication and characterization technologies. This will be achieved through the realization of a variety of micro- and nanoscale structures and devices that can exhibit either classical or quantum effects at the small scale. Although concepts relevant to the laboratories will be emphasized in lecture, it is expected that students will already have been exposed to many of the underlying theoretical concepts of nanotechnology in previous courses. Prerequisite: If course requirement met, permission instructor required.
Course usually offered in spring term
Prerequisite: ESE 525 OR MSE 525
Activity: Lecture
1.0 Course Unit

ESE 539 Hardware/Software Co-Design for Machine Learning
The course is designed to introduce an engineering discipline at the intersection of machine learning and hardware systems to fill the gap. The covered topics include basics of deep learning, deep learning frameworks, deep learning on contemporary computing platforms (CPU, GPU, FPGA) and programmable accelerators (TPU), performance measures, numerical representation and customized data types for deep learning, co-optimization of deep learning algorithms, software and hardware, training for deep learning and complex deep learning models. The course is structured with a combination of lectures, labs, research paper reading/in-class discussion, a final project and guest lectures with state-of-the-art industry practices.
Taught by: Jing Li
Course usually offered in fall term
Prerequisite: CIS 240 AND (ENGR 105 OR CIS 110 OR CIS 120)
Activity: Lecture
1.0 Course Unit

ESE 540 Engineering Economics
This course is cross-listed with an advanced-level undergraduate course (ESE 400). Topics include: money-time relationships, discrete and continuous compounding, equivalence of cash flows, internal and external rate of return, design and production economics, life cycle cost analysis, depreciation, after-tax cash flow analysis, cost of capital, capital financing and allocation, parametric cost estimating models, pricing, foreign exchange rates, stochastic risk analysis, replacement analysis, benefit-cost analysis, and analysis of financial statements. Case studies apply these topics to engineering systems. Students are not required to do additional work compared to ESE 400 students. The work-load is identical.
Course usually offered in fall term
Also Offered As: ESE 400
Activity: Lecture
1.0 Course Unit

ESE 542 Statistics for Data Science
The course covers the methodological foundations of data science, emphasizing basic concepts in statistics and learning theory, but also modern methodologies. Learning of distributions and their parameters. Testing of multiple hypotheses. Linear and nonlinear regression and prediction. Classification. Uncertainty quantification. Model validation. Clustering. Dimensionality reduction. Probably approximately correct (PAC) learning. Such theoretical concepts are further complemented by example applications, case studies (datasets), and programming exercises (in Python) drawn from electrical engineering, computer science, the life sciences, finance, and social networks.
Taught by: Victor Preciado
Course usually offered in fall term
Also Offered As: ESE 402
Prerequisites: ESE 301 or equivalent, CIS 110 or 120
Activity: Lecture
1.0 Course Unit

ESE 543 Human Systems Engineering
This course is an introduction to human systems engineering, examining the various human factors that influence the spectrum of human performance and human systems integration. We will examine both theoretical and practical applications, emphasizing fundamental human cognitive and performance issues. Specific topics include: human performance characteristics related to perception, attention, comprehension, memory, decision making, and the role of automation in human systems integration.
One-term course offered either term
Activity: Lecture
1.0 Course Unit

ESE 544 Project Management
Most work that engineers do is project work and most project work is teamwork. Even when working individually, engineering tasks are usually part of a larger project. This course focuses on developing the sociotechnical knowledge and skills critical to success throughout one's career whether as a project team manager/leader, or a project sponsor. Sociotechnical theory will show us that it doesn't work to focus on the social system or the technical system independent of or in isolation of each other. It is the interplay, the interaction between the behavioral (e.g., communication, conflict management, decision making) and the technical (e.g., SMART goals, scheduling, budgeting, tracking) aspects of project work that most influences project success.
Open systems theory will allow us to examine projects at various system levels: the individual, the team, the organization, and people or groups in the organization’s environment such as suppliers, regulators, competitors, customers and clients.
Taught by: Marcia Wilkof
Two terms. student may enter either term.
Also Offered As: ESE 444
Activity: Lecture
1.0 Course Unit
ESE 545 Data Mining: Learning from Massive Datasets
Many scientific and commercial applications require us to obtain insights from massive, high-dimensional data sets. In this graduate-level course, students will learn to apply, analyze and evaluate principled, state-of-the-art techniques from statistics, algorithms and discrete and convex optimization for learning from such large data sets. The course both covers theoretical foundations and practical applications.
Course usually offered in spring term
Prerequisites: ESE 530, ENM 503
Activity: Lecture
1.0 Course Unit

ESE 546 Principles of Deep Learning
Introductory class in machine learning and optimization. CIS 519, CIS 520, ESE 545, ESE 304, ESE 504, ESE 605 recommended or permission of the instructor.
Course usually offered in fall term
Activity: Lecture
1.0 Course Unit

ESE 547 Introduction to Legged Locomotion
This course reviews three decades’ development of agile legged machines, treating past and recent advances as well as remaining formidable challenges in the materials selection, design, and programming of robots that can run, leap and climb through complicated, unstructured terrain. Emphasis is on developing understanding of and facility using key dynamical primitives whose composition allows more complicated behaviors to emerge from simpler constituents. Several historical case studies will be used to illustrate how advances have rewarded interdisciplinary thinking about animals, materials, mathematics and mechatronics. Course credit will be based on problem sets and coding exercises.
Taught by: D. E. Koditschek
Activity: Lecture
1.0 Course Unit

ESE 548 Transportation Planning Methods
This course introduces students to the development and uses of the 4-step urban transportation model (trip generation-trip distribution-mode choice-traffic assignment) for community and metropolitan mobility planning. Using the VISUM transportation desktop planning package, students will learn how to build and test their own models, apply them to real projects, and critique the results. Prerequisite: CPLN 505 or other planning statistics course.
Taught by: Ryerson
Course usually offered in spring term
Also Offered As: CPLN 560
Prerequisite: CPLN 505
Activity: Lecture
1.0 Course Unit

ESE 550 Advance Transportation Seminar
Air transportation is a fascinating multi-disciplinary area of transportation bringing together business, planning, engineering, and policy. In this course, we explore the air transportation system from multiple perspectives through a series of lessons and case studies. Topics will include airport and intercity multimodal environmental planning, network design and reliability, air traffic management and recovery from irregular operations, airline operations, economics, and fuel, air transportation sustainability, and land use issues related to air transportation systems. This course will introduce concepts in economics and behavioral modeling, operations research, statistics, environmental planning, and human factors that are used in aviation and are applicable to other transportation systems. The course will emphasize learning through lessons, guest lecturers, case studies of airport development and an individual group and research project.
Taught by: Ryerson
Course usually offered in spring term
Also Offered As: CPLN 750
Prerequisite: CPLN 550
Activity: Seminar
1.0 Course Unit

ESE 566 Networked Neuroscience
The human brain produces complex functions using a range of system components over varying temporal and spatial scales. These components are coupled together by heterogeneous interactions, forming an intricate information-processing network. In this course, we will cover the use of network science in understanding such large-scale and neuronal-level brain circuitry. Prerequisite: Graduate standing or permission of the instructor. Experience with Linear Algebra and MATLAB.
Course usually offered in spring term
Also Offered As: BE 566
Activity: Lecture
1.0 Course Unit

ESE 567 Risk Analysis and Environmental Management
This course will introduce students to concepts in risk governance. We will delve into the three pillars of risk analysis: risk assessment, risk management, and risk communication. The course will spend time on risk financing, including insurance markets. There will be particular emphasis on climate risk management, including both physical impact risk and transition risk, although the course will also discuss several other examples, including management of environmental risks, terrorism, and cyber-security, among other examples. The course will cover how people perceive risks and the impact this has on risk management. We will explore public policy surrounding risk management and how the public and private sector can successfully work together to build resilience, particularly to changing risks.
One-term course offered either term
Also Offered As: BEPP 261, BEPP 761, BEPP 961, OIDD 261, OIDD 761
Activity: Lecture
1.0 Course Unit
ESE 570 Digital Integrated Circuits and VLSI-Fundamentals
Explores the design aspects involved in the realization of an integrated circuit from device up to the register/subsystem level. It addresses major design methodologies with emphasis placed on the structured design. The course includes the study of MOS device characteristics, the critical interconnect and gate characteristics which determine the performance of VLSI circuits, and NMOS and CMOS logic design. Students will use state-of-the-art CAD tools to verify designs and develop efficient circuit layouts.
Course usually offered in spring term
Prerequisite: ESE 319
Activity: Lecture
1.0 Course Unit

ESE 572 Analog Integrated Circuits
Design of analog circuits and subsystems using bipolar and MOS technologies at the transistor and higher levels. Transistor level design of building block circuits such as op amps, comparators, sample and hold circuits, voltage and current references, capacitors and resistor arrays, and class AB output stages. The course will include a design project of an analog circuit. The course will use the Cadence Design System for schematic capture and simulation with Spectre circuit simulator. This course is similar to ESE 570, except that it will not require the use of the physical layout tools associated with VLSI design and implementation.
Course usually offered in fall term
Also Offered As: ESE 419
Prerequisite: ESE 319
Activity: Lecture
1.0 Course Unit

ESE 574 The Principles and Practice of Microfabrication Technology
A laboratory-based course on fabricating microelectronic and micromechanical devices using photolithographic processing and related fabrication technologies. Lectures discuss: clean room procedures; microelectronic and microstructural materials; photolithography; diffusion, oxidation; materials deposition; etching and plasma processes. Basic laboratory processes are covered for the first two thirds of the course with students completing structures appropriate to their major in the final third. Students registering for ESE 574 will be expected to do extra work (including term paper and additional project).
Course not offered every year
Also Offered As: ESE 460, MEAM 564
Prerequisites: ESE 218, MSE 321, MEAM 333, CBE 351, PHYS 250
Activity: Lecture
1.0 Course Unit

ESE 578 RFIC (Radio Frequency Integrated Circuit) Design
Introduction to RF (Radio Frequency) and Microwave Theory, Components, and Systems. The course aims at providing knowledge in RF transceiver design at both microwave and millimeter-wave frequencies. Both system and circuit level perspective will be addressed, supported by modeling and simulation using professional tools (including Agilent ADS, Sonnet, and Cadence Design Systems). Topics include: Transmission Line Theory, S-parameters, Smith Chart for matching network design, stability, noise, and mixed signal design. RF devices covered will include: hybrid/Wilkinson/Lange 3dB couplers, Small Signal Amplifiers (SSA), Low Noise Amps (LNA), and Power Amps (PA). CMOS technology will be largely used to design the devices mentioned.
Course usually offered in spring term
Prerequisite: ESE 572
Activity: Lecture
1.0 Course Unit

ESE 590 Systems Methodology
This course covers the methodologies and techniques important to designing large complex, purposeful systems and to discovering policies that influence them throughout the stages of their lifecycle. The course focuses on hands-on synthetic thinking, where students assemble the big picture from modeling the individual actors, organizations, and artifacts in a socio-technical system of interest. This is the study of emergence of macro-behavior from the micro-decision making of the actors involved - to inquire into the design of a purposeful system, and to examine alternative futures that are ideal, yet affordable, sustainable, and workable. Specifically, the student learns systems theory, systems methodologies (design inquiry/learning systems, idealized design/interactive planning, and soft systems methodology/knowledge management), bottom up modeling (decision science, multi-attribute utility theory, affective reasoning, agent based modeling, simulated societies), and how to further research and apply the synthetic paradigm.
Course usually offered in fall term
Activity: Lecture
1.0 Course Unit

ESE 597 Master's Thesis
One-term course offered either term
Activity: Masters Thesis
1.0 Course Unit

ESE 599 Independent Study for Master's credit
One-term course offered either term
Activity: Independent Study
1.0 Course Unit

ESE 605 Modern Convex Optimization
This course concentrates on recognizing and solving convex optimization problems that arise in engineering. Topics include: convex sets, functions, and optimization problems. Basis of convex analysis. Linear, quadratic, geometric, and semidefinite programming. Optimality conditions, duality theory, theorems of alternative, and applications. Interior-point methods, ellipsoid algorithm and barrier methods, self-concordance. Applications to signal processing, control, digital and analog circuit design, computation geometry, statistics, and mechanical engineering. Knowledge of linear algebra and willingness to do programming.
Course usually offered in spring term
Activity: Lecture
1.0 Course Unit

ESE 611 Nanophotonics: Light at the Nanoscale
This course is intended for first and second year graduate students interested in nanoscale optics and photonics. Building on prior coursework in electromagnetism, this course provides a theoretical foundation and up-to-date survey of the key principles and phenomena relevant to the field of nanophotonics. Topics discussed include light-matter interaction through Maxwell’s equations, photonic band theory and photonic crystals, plasmonic structures and devices, metamaterials and metasurfaces, PT-symmetric & topological photonic systems. Applications of nanophotonic devices and principles to a wide range of scenarios will also be explored in depth, including for renewable energy, information processing, imaging and sensing. Experimental techniques used in nanophotonics will be concurrently introduced and discussed.
Prerequisite: Permission of instructor
One-term course offered either term
Activity: Lecture
1.0 Course Unit
**ESE 615 F1/10 Autonomous Racing Cars**
This hands-on, lab-centered course is for senior undergraduates and graduate students interested in the fields of artificial perception, motion planning, control theory, and applied machine learning. It is also for students interested in the burgeoning field of autonomous driving. This course introduces the students to the hardware, software and algorithms involved in building and racing an autonomous race car. Every week, students take two lectures and complete an extensive hands-on lab. By Week 6, the students will have built, programmed and driven a 1/10th scale autonomous race car. By Week 10, the students will have learned fundamental principles in perception, planning and control and will race using map-based approaches. In the last 6 weeks, they develop and implement advanced racing strategies, computer vision and machine learning algorithms that will give their team the edge in the race that concludes the course. Prerequisites: C++ and Python programming, Matrix algebra, Differential equations, Signals and Systems
Taught by: Rahul Mangharam
Activity: Lecture
1.0 Course Unit

**ESE 617 Non-Linear Control Theory**
The course provides a basic understanding of nonlinear systems phenomena and studies analysis and control design problems of nonlinear systems. The main analysis tools that will be presented are Lyapunov theory for stability, including the well known LaSalle’s invariance principle, and barrier function theory for safety of both autonomous and non-autonomous systems. Further topics include input-output stability, passivity, and the center manifold theorem. The main control tools that will be presented are feedback linearization, backstepping, as well as recent results on learning control Lyapunov and control barrier functions from data. Examples will be taken from mechanical and robotic systems.
Taught by: Lars Lindemann
Course not offered every year
Also Offered As: MEAM 613
Prerequisite: ESE 500
Activity: Lecture
1.0 Course Unit

**ESE 618 Learning for Dynamics and Control**
This course will provide students an introduction to the emerging area at the intersection of machine learning, dynamics, and control. We will investigate machine learning and data-driven algorithms that interact with the physical world, with an emphasis on a holistic understanding of the interplay between concepts from control theory (e.g., feedback, stability, robustness) and machine learning (e.g., generalization, sample-complexity). Topics of study will include learning models of dynamical systems, using these models to robustly meet performance objectives, optimally refining models to improve performance, and verifying the safety of machine learning enabled control systems. The course will also expose students to the ethical considerations that need to be considered when designing learning algorithms that interact with and are placed in feedback with the world. The course will consist of lectures, and students will be evaluated based on traditional and programming assignments, as well as a final project.
Taught by: Nikolai Matni
Course usually offered in fall term
Prerequisite: ESE 500 AND ESE 530
Activity: Lecture
1.0 Course Unit

**ESE 619 Model Predictive Control**
Increased system complexity and more demanding performance requirements have rendered traditional control laws inadequate regardless if simple PID loops are considered or robust feedback controllers designed according to some H2/infinity criterion. Applications ranging from the process industries to the automotive and the communications sector are making increased use of Model Predictive Control (MPC) where a fixed control law is replaced by on-line optimization performed over a receding horizon. The advantage is that MPC can deal with almost any time-varying process and specifications, limited only by the availability of real-time computer power. In the last few years we have seen tremendous progress in this interdisciplinary area where fundamentals of systems theory, computation and optimization interact. For example, methods have emerged to handle hybrid systems, i.e. systems comprising both continuous and discrete components. Also, it is now possible to perform most of the computations off-line thus reducing the control law to a simple look-up table.
Course usually offered in spring term
Prerequisites: ESE 500, 504 or 605
Activity: Lecture
1.0 Course Unit

**ESE 621 Nanoelectronics**
This is a graduate level course on fundamental operating principles and physics of semiconductor devices in reduced or highly scaled dimensions. The course will include topics and concepts covering basic quantum mechanics and solid state physics of nanostructures as well as device transport and characterization, materials and fabrication. A basic knowledge of semiconductor physics and devices is assumed. The course will build upon basic quantum mechanics and solid state physics concepts to understand the operation of nanoscale semiconductor devices and physics of electrons in confined dimensions. The course will also provide a historical perspective on micro and nanoelectronics, discuss the future of semiconductor computing technologies, cutting edge research in nanomaterials, device fabrication as well as provide a perspective on materials and technology challenges. Prerequisite: If course requirement not met, permission of instructor required.
Course usually offered in spring term
Prerequisite: ESE 521
Activity: Lecture
1.0 Course Unit

**ESE 625 Nanorobotics**
Nanorobotics is a field at the forefront of nano-science and engineering that seeks to create synthetic systems that sense and respond to their environment at dimensions comparable to biological microorganisms. This course explores the topic of small machines: What materials should we use to make these devices? How should they be powered or locomote? What capacities can they have for memory or information processing? How can they be made to interface safely with biological systems? This course covers the major frameworks for building small machines, including self-assembled systems (DNA nanotechnology, biohacking) and those fabricated by top-down lithography (self-folding systems, synthetic micro-swimmers, smart-dust). Particular emphasis is given to exploring physical principles that can be used to analyze the strengths and limitations of current robot designs at the micro and nanoscale.
Taught by: Marc Miskin
Activity: Lecture
1.0 Course Unit
ESE 635 Distributed Systems
This research seminar deals with tools, methods, and algorithms for analysis and design of distributed dynamical systems. These are large collections of dynamical systems that are spatially interconnected to form a collective task or achieve a global behavior using local interactions. Over the past decade such systems have been studied in disciplines as diverse as statistical physics, computer graphics, robotics, and control theory. The purpose of this course is to build a mathematical foundation for study of such systems by exploring the interplay of control theory, distributed optimization, dynamical systems, graph theory, and algebraic topology. Assignments will consist of reading and researching the recent literature in this area. Topics covered in distributed coordination and consensus algorithms over networks, coverage problems, effects of delay in large scale networks, Power law graphs, gossip and consensus algorithms, synchronization phenomena in natural and engineered systems, etc.
Course not offered every year
Prerequisites: Basic knowledge of linear systems (ESE 500), linear algebra (MATH 312 or equivalent), and optimization (ESE 504 or equivalent) and some familiarity with basics of nonlinear systems (ESE 617 or equivalent). Students without this background should consult with the instructor before registering.
Activity: Lecture
1.0 Course Unit

ESE 650 Learning in Robotics
This course will cover the mathematical fundamentals and applications of machine learning algorithms to mobile robotics. Possible topics that will be discussed include probabilistic generative models for sensory feature learning. Bayesian filtering for localization and mapping, dimensionality reduction techniques for motor control, and reinforcement learning of behaviors. Students are expected to have a solid mathematical background in machine learning and signal processing, and will be expected to implement algorithms on a mobile robot platform for their course projects. Grading will be based upon course project assignments as well as class participation. Students will need permission from the instructor. They will be expected to have a good mathematical background with knowledge of machine learning techniques at the level of CIS 520, signal processing techniques at the level of ESE 531, as well as have some robotics experience.
Course usually offered in spring term
Activity: Lecture
1.0 Course Unit

ESE 668 Mixed Signal Circuit Design and Modeling
This course will introduce design and analysis of mixed-signal integrated circuits. Topics include: Sampling and quantization, Sampling circuits, Switched capacitor circuits and filters, Comparators, Offset compensation, DACs/ADCS (Flash, delta-sigma, pipeline, SAR), Oversampling, INL/DNL, FOM. The course will end with a final design project using analysis and design techniques learned in the course. Students must provide a written report with explanations to their design choices either with equations or simulation analysis/insight along with performance results.
Taught by: Tania Khanna
Course usually offered in spring term
Prerequisite: ESE 419 OR ESE 572
Activity: Lecture
1.0 Course Unit

ESE 672 Integrated Communication Systems
This is an advanced radio frequency (RF) circuit design course that includes analysis and design of high-frequency and high-speed integrated communication circuits at both transistor and system levels. Students gradually design and simulate different blocks of an RF receiver and combine these blocks to form the receiver as their final project. We assume some background knowledge of device physics, electromagnetics, circuit theory, control theory, and stochastic processes.
One-term course offered either term
Prerequisite: ESE 419 OR ESE 572
Activity: Lecture
1.0 Course Unit

ESE 673 Integrated Photonic Systems
Analysis and design of photonic integrated systems at both device and system levels including architectures, photonic integrated circuit technologies, passive components (nano-waveguides, resonators, couplers, and Y-junctions) and active components (lasers, modulators, and photodiodes) are studied. The emphasis is on silicon photonics.
Prerequisite: If course requirement not met, permission of instructor required.
Course usually offered in spring term
Prerequisite: ESE 510
Activity: Lecture
1.0 Course Unit

ESE 674 Information Theory
Deterministic and probabilistic information. The pigeon-hole principle. Entropy, relative entropy, and mutual information. Random processes and entropy rate. The asymptotic equipartition property. Optimal codes and data compression. Channel capacity. Source channel coding. The ubiquitous nature of the theory will be illustrated with a selection of applications drawn from among: universal source coding, vector quantization, network communication, the stock market, hypothesis testing, algorithmic computation and kolmogorov complexity, and thermodynamics.
Course not offered every year
Prerequisite: ESE 530
Activity: Lecture
1.0 Course Unit

ESE 676 Coding Theory
Coding theory for telecommunications with emphasis on the algebraic theory of cyclic codes using finite field arithmetic, decoding of BCH and Reed-Solomon codes, finite field Fourier transform and algebraic geometry codes, convolutional codes and trellis decoding algorithms, graph based codes, Berrou codes and Gallager codes, turbo decoding, iterative decoding. And belief propagation.
Course not offered every year
Prerequisites: ESE 224, MATH 240, PHYS 150
Activity: Lecture
1.0 Course Unit

ESE 680 Special Topics in Electrical and Systems Engineering
Advanced and specialized topics in both theory and application areas. Students should check Graduate Group office for offerings during each registration period.
Course not offered every year
Activity: Lecture
1.0 Course Unit
ESE 895 Teaching Practicum
Participation of graduate students in the teaching mission of the department will help to develop teaching, presentation, leadership, and interpersonal skills while assisting the department in discharging its teaching responsibilities. All doctoral students are required to participate under faculty guidance in the teaching mission of the department. This requirement will be satisfied by completing two 0.5 course units of teaching practicum (ESE 895). Each 0.5 course unit of teaching practicum will consist of the equivalent of 10 hours of effort per week for one semester. As a part of the preparation for and fulfillment of the teaching practicum requirement, the student will attend seminars emphasizing teaching and communication skills, lead recitations, lead tutorials, supervise laborato experiments, develop instructional laboratories, develop instructional materiaand grade homeworks, laboratory reports, and exams. A teacher training seminar will be conducted the day before the first day of classes of the Fall semester. Attendance is mandatory for all second-year students. As much as possible, the grading aspect of the teaching practicum course will be such as not to exceed 50% of the usual teaching assistant commitment time. Some of the recitations will b supervised and feedback and comments will be provided to the student by the faresponsible for the course. At the completion of every 0.5 course unit of teach, the student will receive a Satisfactory/Unsatisfactory grade and a written evsigned by the faculty member responsible for the course. The evaluation will beon comments of the students taking the course and the impressions of the facult
One-term course offered either term
Activity: Lecture
0.5 Course Units

ESE 899 Independent Study for PhD credit
For students who are studying a specific advanced subject area in electrical engineering. Students must submit a proposal outlining and detailing the study area, along with the faculty supervisor's consent, to the graduate group chair for approval. A maximum of 1 c.u. of ESE 899 may be applied toward the MSE degree requirements. A maximum of 2 c.u.'s of ESE 899 may be applied toward the Ph.D. degree requirements.
One-term course offered either term
Activity: Independent Study
1.0 Course Unit

ESE 995 Dissertation
Register for this after completing four years of full-time study including two course units each Summer Session (and usually equal to 40 course units).
One-term course offered either term
Activity: Dissertation
1.0 Course Unit

ESE 999 Thesis/Dissertation Research
For students working on an advanced research program leading to the completion of master's thesis or Ph.D. dissertation requirements.
One-term course offered either term
Activity: Independent Study
1.0 Course Unit