Computer Science & Engineering

During the past two decades, society has experienced unprecedented growth in digital technology. This revolution continues to redefine our way of life, our culture and our economy. Computer science and engineering education plays an irreplaceable role in this trend by preparing future technology leaders and innovators. It opens our minds to new horizons, unlocks doors to a broad range of career paths, accelerates professional advancement, and exposes us to ideas that are advancing the frontiers of science and technology beyond the field of computing. Alumni and students continually remind us that pursuing a degree in the Department of Computer Science & Engineering is an experience rarely matched elsewhere.

Master's Programs

The Department of Computer Science & Engineering offers four master's degrees: Master of Science in Computer Science, Master of Science in Computer Engineering, Master of Science in Cybersecurity Engineering, and Master of Engineering in Computer Science and Engineering. We accept both full-time and part-time students, offering class schedules that are flexible enough for part-time students but that provide enough classes for students to attend full-time. Obtaining a master's degree from the Department of Computer Science & Engineering can be done as a pure course option (MS in Computer Science and MS in Computer Engineering degrees only), or it can incorporate a specialized research experience. Master's research is a great way for our students to easily transition into future doctoral studies. Graduates of our program are also prepared to enter the industry, with many accepting positions at companies like Boeing, Google and Microsoft. Applicants to our master's programs are expected to have completed an undergraduate degree. A major or minor in computer science or computer engineering is helpful, but it is not required. Background requirements are listed within each degree program, along with options for meeting them.

PhD Programs

The Department of Computer Science & Engineering offers PhD programs in Computer Science and in Computer Engineering. Computer science research encompasses the fundamentals of software and algorithm design, machine learning and bioinformatics, visual and cyber-physical computing, and human-computer interaction. Computer engineering focuses on the interaction of software and hardware in the design of computing systems and networks. Our research groups have extensive interdisciplinary ties across the university, with collaborations in medicine, science, the humanities and social work. Recent graduates have accepted research and teaching faculty positions as well as research and engineering positions in leading technology companies.

Both PhD programs require a combination of courses, research and teaching. The required courses are often completed early in the program, since students are integrated into research groups during their first year and the program's emphasis is on creative research. The program has milestones that involve both written and oral components, and these provide structure for the five- to six-year degree. The program considers applicants with either bachelor's or master's degrees and has had successful applicants in the past whose backgrounds were outside of the field of computer science.

Phone: 314-935-6132
Email: admissions@cse.wustl.edu
Website: https://cse.wustl.edu/graduate/

Faculty

Chair

Roch Guérin (https://engineering.wustl.edu/Profiles/Pages/Roch-Gu%C3%A9rin.aspx)
Harold B. and Adelaide G. Welge Professor of Computer Science
PhD, California Institute of Technology
Computer networks and communication systems

Professors

Sanjoy Baruah (https://engineering.wustl.edu/Profiles/Pages/Sanjoy-Baruah.aspx)
PhD, University of Texas at Austin
Real-time and safety-critical system design, cyber-physical systems, scheduling theory, resource allocation and sharing in distributed computing environments

Aaron Bobick (https://engineering.wustl.edu/Profiles/Pages/Aaron-Bobick.aspx)
James M. McKelvey Professor and Dean
PhD, Massachusetts Institute of Technology
Computer vision, graphics, human-robot collaboration

Michael R. Brent (https://engineering.wustl.edu/Profiles/Pages/Michael-Brent.aspx)
Henry Edwin Sever Professor of Engineering
PhD, Massachusetts Institute of Technology
Systems biology, computational and experimental genomics, mathematical modeling, algorithms for computational biology, bioinformatics

Jeremy Buhler (https://engineering.wustl.edu/Profiles/Pages/Jeremy-Buhler.aspx)
PhD, Washington University
Computational biology, genomics, algorithms for comparing and annotating large biosequences
Roger D. Chamberlain (https://engineering.wustl.edu/Profiles/Pages/Roger-Chamberlain.aspx)
DSc, Washington University
Computer engineering, parallel computation, computer architecture, multiprocessor systems

Yixin Chen (https://engineering.wustl.edu/Profiles/Pages/Yixin-Chen.aspx)
PhD, University of Illinois at Urbana-Champaign
Mathematical optimization, artificial intelligence, planning and scheduling, data mining, learning data warehousing, operations research, data security

Patrick Crowley (https://engineering.wustl.edu/Profiles/Pages/Patrick-Crowley.aspx)
PhD, University of Washington
Computer and network systems, network security

Ron K. Cytron (https://engineering.wustl.edu/Profiles/Pages/Ron-Cytron.aspx)
PhD, University of Illinois at Urbana-Champaign
Programming languages, middleware, real-time systems

Christopher D. Gill (https://engineering.wustl.edu/Profiles/Pages/Christopher-Gill.aspx)
DSc, Washington University
Parallel and distributed real-time embedded systems, cyber-physical systems, concurrency platforms and middleware, formal models and analysis of concurrency and timing

Raj Jain (https://engineering.wustl.edu/Profiles/Pages/Raj-Jain.aspx)
Barbara J. & Jerome R. Cox Jr. Professor of Computer Science
PhD, Harvard University
Network security, blockchains, medical systems security, industrial systems security, wireless networks, unmanned aircraft systems, internet of things, telecommunications networks, traffic management

Tao Ju (https://engineering.wustl.edu/Profiles/Pages/Tao-Ju.aspx)
PhD, Rice University
Computer graphics, visualization, mesh processing, medical imaging and modeling

Chenyang Lu (https://engineering.wustl.edu/Profiles/Pages/Chenyang-Lu.aspx)
Fullgraf Professor in the Department of Computer Science & Engineering
PhD, University of Virginia
Internet of things, real-time, embedded, and cyber-physical systems, cloud and edge computing, wireless sensor networks

Neal Patwari (https://engineering.wustl.edu/Profiles/Pages/Neal-Patwari.aspx)
PhD, University of Michigan
Application of statistical signal processing to wireless networks, and radio frequency signals

Weixiong Zhang
PhD, University of California, Los Angeles
Computational biology, genomics, machine learning and data mining, and combinatorial optimization

Associate Professors

Kunal Agrawal (https://engineering.wustl.edu/Profiles/Pages/Kunal-Agrawal.aspx)
PhD, Massachusetts Institute of Technology
Parallel computing, cyber-physical systems & sensing, theoretical computer science

Sanmay Das (https://engineering.wustl.edu/Profiles/Pages/Sanmay-Das.aspx)
PhD, Massachusetts Institute of Technology
Design of algorithms for complex environments, computational social science, machine learning

Caitlin Kelleher (https://engineering.wustl.edu/Profiles/Pages/Caitlin-Kelleher.aspx)
Hugo F. & Ina Champ Urbauer Career Development Associate Professor
PhD, Carnegie Mellon University
Human-computer interaction, programming environments, and learning environments

William D. Richard (https://engineering.wustl.edu/Profiles/Pages/William-Richard.aspx)
PhD, University of Missouri-Rolla
Ultrasonic imaging, medical instrumentation, computer engineering

Yevgeniy Vorobeychik (https://cse.wustl.edu/faculty/Pages/faculty.aspx?bio=185)
PhD, University of Michigan
Artificial intelligence, machine learning, computational economics, security and privacy, multi-agent systems

Assistant Professors

Ayan Chakrabarti (https://engineering.wustl.edu/Profiles/Pages/Ayan-Chakrabarti.aspx)
PhD, Harvard University
Computer vision computational photography, machine learning

Roman Garnett (https://engineering.wustl.edu/Profiles/Pages/Roman-Garnett.aspx)
PhD, University of Oxford
Active learning (especially with atypical objectives), Bayesian optimization, and Bayesian nonparametric analysis

Chien-Ju Ho (https://engineering.wustl.edu/Profiles/Pages/Chien-Ju-Ho.aspx)
PhD, University of California, Los Angeles
Design and analysis of human-in-the-loop systems, with techniques from machine learning, algorithmic economics, and online behavioral social science
Brendan Juba
PhD, Massachusetts Institute of Technology
Theoretical approaches to artificial intelligence founded on computational complexity theory and theoretical computer science more broadly construed

Ulugbek Kamilov
PhD, École Polytechnique Fédérale de Lausanne, Switzerland
Computational imaging, image and signal processing, machine learning and optimization

Brian Kocoloski
PhD, University of Pittsburgh
Scalable parallel computing, cloud computing, operating systems, virtualization

Angelina Lee
PhD, Massachusetts Institute of Technology
Designing linguistics for parallel programming, developing runtime system support for multithreaded software, and building novel mechanisms in operating systems and hardware to efficiently support parallel abstractions

Alvitta Ottley
PhD, Tufts University
Designing personalized and adaptive visualization systems, including information visualization, human-computer interaction, visual analytics, individual differences, personality, user modeling and adaptive interfaces

William Yeoh
PhD, University of Southern California
Artificial intelligence, multi-agent systems, distributed constraint optimization, planning and scheduling

Miaomiao Zhang
PhD, University of Utah
Medical image analysis, statistical modeling, and machine learning

Ning Zhang
PhD, Virginia Polytechnic Institute and State University
System security, software security

Lecturers

Steve Cole, Senior Lecturer
PhD, Washington University in St. Louis
Parallel computing, accelerating streaming applications on GPUs

Marion Neumann, Senior Lecturer
PhD, University of Bonn, Germany
Machine learning with graphs; solving problems in agriculture and robotics

Jonathan Shidal, Lecturer
PhD, Washington University
Computer architecture and memory management

Douglas Shook, Lecturer
MS, Washington University
Imaging sensor design, compiler design and optimization

William Siever, Principal Lecturer
PhD, Missouri University of Science and Technology
Computer architecture, organization, and embedded systems

Todd Sproull, Senior Lecturer
PhD, Washington University
Computer networking and mobile application development

Senior Professors

Jerome R. Cox Jr.
ScD, Massachusetts Institute of Technology
Computer system design, computer networking, biomedical computing

Jonathan S. Turner
PhD, Northwestern University
Design and analysis of internet routers and switching systems, networking and communications, algorithms

Professors Emeriti

Takayuki D. Kimura
PhD, University of Pennsylvania
Communication and computation, visual programming

Seymour V. Pollack
MS, Brooklyn Polytechnic Institute
Intellectual property, information systems

Degree Requirements

Please visit to the following pages for information about computer science and engineering graduate programs:

- PhD in Computer Science or Computer Engineering (http://bulletin.wustl.edu/grad/engineering/computerscience/phd)
• Master of Science (MS) in Computer Science (http://bulletin.wustl.edu/grad/engineering/computerscience/ms-computer-science)
• Master of Science (MS) in Computer Engineering (http://bulletin.wustl.edu/grad/engineering/computerscience/ms-computer-engineering)
• Master of Science (MS) in Cybersecurity Engineering (http://bulletin.wustl.edu/grad/engineering/computerscience/ms-cybersecurity)
• Master of Engineering (MEng) in Computer Science and Engineering (http://bulletin.wustl.edu/grad/engineering/computerscience/meng-computer-science)
• Certificate in Data Mining and Machine Learning (http://bulletin.wustl.edu/grad/engineering/computerscience/certificate-data-mining-machine-learning)

Courses

Visit online course listings to view semester offerings for E81 CSE (https://courses.wustl.edu/CourseInfo.aspx?sch=E&dept=E81&crslvl=5:8).

E81 CSE 500 N Independent Study
Proposal form can be located at https://cse.wustl.edu/undergraduate/PublishingImages/Pages/undergraduate-research/Independent%20Study%20Form%20400.pdf Credit variable, maximum 3 units.

E81 CSE 501 N Introduction to Computer Science
An introduction to software concepts and implementation, emphasizing problem solving through abstraction and decomposition. Introduces processes and algorithms, procedural abstraction, data abstraction, encapsulation, and object-oriented programming. Recursion, iteration, and simple data structures are covered. Concepts and skills are mastered through programming projects, many of which employ graphics to enhance conceptual understanding. Java, an object-oriented programming language, is the vehicle of exploration. Active-learning sessions are conducted in a studio setting in which students interact with each other and the professor to solve problems collaboratively. Prerequisites: Comfort with algebra and geometry at the high school level is assumed. Patience, good planning, and organization will promote success. This course assumes no prior experience with programming. Same as E81 CSE 131 Credit 3 units. BU: SCI EN: TU

E81 CSE 502 N Data Structures and Algorithms
This course involves the study of fundamental algorithms, data structures, and their effective use in a variety of applications. It emphasizes the importance of data structure choice and implementation for obtaining the most efficient algorithm for solving a given problem. A key component of this course is worst-case asymptotic analysis, which provides a quick and simple method for determining the scalability and effectiveness of an algorithm. Prerequisite: CSE 131. Same as E81 CSE 247 Credit 3 units. EN: TU

E81 CSE 503 S Rapid Prototype Development and Creative Programming
This course uses web development as a vehicle for developing skills in rapid prototyping. Students acquire the skills to build a Linux web server in Apache, to write a website from scratch in PHP, to run an SQL database, to perform scripting in Python, to employ various web frameworks, and to develop modern web applications in client-side and server-side JavaScript. The course culminates with a creative project in which students are able to synthesize the course material into a project of their own interest. The course implements an interactive studio format: after the formal presentation of a topic, students develop a related project under the supervision of the instructor. Prerequisite: CSE 131. Same as E81 CSE 330 S Credit 3 units. EN: BME T, TU

E81 CSE 504 N Object-Oriented Software Development Laboratory
Intensive focus on practical aspects of designing, implementing and debugging software, using object-oriented, procedural, and generic programming techniques. The course emphasizes familiarity and proficiency with a wide range of C++ language features through hands-on practice completing studio exercises and lab assignments, supplemented with readings and summary presentations for each session. Prerequisites: CSE 247. Same as E81 CSE 332 S Credit 3 units. EN: BME T, TU

E81 CSE 505 N Introduction to Digital Logic and Computer Design
Introduction to design methods for digital logic and fundamentals of computer architecture. Boolean algebra and logic minimization techniques; sources of delay in combinational circuits and effect on circuit performance; survey of common combinational circuit components; sequential circuit design and analysis; timing analysis of sequential circuits; use of computer-aided design tools for digital logic design (schematic capture, hardware description languages, simulation); design of simple processors and memory subsystems; program execution in simple processors; basic techniques for enhancing processor performance; configurable logic devices. Prerequisite: CSE 131. Same as E81 CSE 260 M Credit 3 units. EN: TU

E81 CSE 507 A Technology Entrepreneurship
This is a course for students who plan to be or to work with entrepreneurs. An entrepreneurial mindset is needed to create or grow economically viable enterprises, be they new companies, new groups within companies, or new university laboratories. This course aims to cultivate an entrepreneurial perspective, with particular emphasis on information technology (IT)-related activities. The course is jointly offered for business and CSE students, allowing for acculturation between these disciplines. In addition to an introductory treatment of business and technology fundamentals, course topics will include business ethics, opportunity assessment, team formation, financing, intellectual property, and technology transfer. The course will feature significant participant and guest instruction from experienced practitioners. Credit 3 units.

E81 CSE 507 A Technology Entrepreneurship
This is a course for students who plan to be or to work with entrepreneurs. An entrepreneurial mindset is needed to create or grow economically viable enterprises, be they new companies, new groups within companies, or new university laboratories. This course aims to cultivate an entrepreneurial perspective, with particular emphasis on information technology (IT)-related activities. The course is jointly offered for business and CSE students, allowing for acculturation between these disciplines. In addition to an introductory treatment of business and technology fundamentals, course topics will include business ethics, opportunity assessment, team formation, financing, intellectual property, and technology transfer. The course will feature significant participant and guest instruction from experienced practitioners. Credit 3 units.
E81 CSE 511A Introduction to Artificial Intelligence
The discipline of artificial intelligence (AI) is concerned with building systems that think and act like humans or rationally on some absolute scale. This course is an introduction to the field, with special emphasis on sound modern methods. The topics include knowledge representation, problem solving via search, game playing, logical and probabilistic reasoning, planning, dynamic programming, and reinforcement learning. Programming exercises concretize the key methods. The course targets graduate students and advanced undergraduates. Evaluation is based on written and programming assignments, a midterm exam and a final exam. Prerequisites: CSE 247, ESE 326, Math 233. Credit 3 units.

E81 CSE 515T Bayesian Methods in Machine Learning
This course will cover machine learning from a Bayesian probabilistic perspective. Bayesian probability allows us to model and reason about all types of uncertainty. The result is a powerful, consistent framework for approaching many problems, including parameter estimation, model comparison, and decision making. We will begin with a high-level introduction to Bayesian inference, then proceed to cover more-advanced topics. These will include inference techniques (exact, MAP, sampling methods, the Laplace approximation, etc.), Bayesian decision theory, Bayesian model comparison, Bayesian nonparametrics, and Bayesian optimization. Prerequisites: CSE 417T. Credit 3 units.

E81 CSE 516A Multi-Agent Systems
This course introduces the fundamental techniques and concepts needed to study multi-agent systems, in which multiple autonomous entities with different information sets and goals interact. We will study algorithmic, mathematical, and game-theoretic foundations, and how these foundations can help us understand and design systems ranging from robot teams to online markets to social computing platforms. Topics covered may include game theory, distributed optimization, multi-agent learning and decision-making, preference elicitation and aggregation, mechanism design, and incentives in social computing systems. Prerequisites: CSE 347 (may be taken concurrently), ESE 326 (or Math 3200), and Math 233 or equivalents. Some prior exposure to artificial intelligence, machine learning, game theory, and microeconomics may be helpful, but is not required. Credit 3 units.

E81 CSE 517A Machine Learning
This course assumes a basic understanding of machine learning and covers advanced topics at the frontier of the field in-depth. Topics to be covered include kernel methods (support vector machines, Gaussian processes), neural networks (deep learning), and unsupervised learning. Depending on developments in the field, the course will also cover some advanced topics, which may include learning from structured data, active learning, and practical machine learning (feature selection, dimensionality reduction). Prerequisites: CSE 417T. Credit 3 units.

E81 CSE 517B Advanced Machine Learning
This course provides a close look at advanced machine learning algorithms — their theoretical guarantees (computational learning theory) and tricks to make them work in practice. In addition, this course focuses on more specialized learning settings, including unsupervised learning, semi-supervised learning, domain adaptation, multi-task learning, structured prediction, metric learning and learning of data representations. Learning approaches may include graphical models, non-parametric Bayesian statistics, and technical topics such as sampling, approximate inference and non-linear function optimization. Mathematical maturity and general familiarity of machine learning is required. Prerequisites: CSE 247, ESE 326, Math 233, and Math 309. Credit 3 units.

E81 CSE 518A Human-in-the-Loop Computation
This course is an exploration of the opportunities and challenges of human-in-the-loop computation, an emerging field that examines how humans and computers can work together to solve problems neither can yet solve alone. We will explore ways in which techniques from machine learning, game theory, optimization, online behavioral social science, and human-computer interactions can be used to model and analyze human-in-the-loop systems such as crowdsourcing markets, prediction markets, and user-generated content platforms. We will also look into recent developments in the interactions between humans and AIs, such as learning with the presence of strategic behavior and ethical issues in AI systems. Prerequisites: CSE 247, ESE 326, Math 233, and Math 309. Credit 3 units.
middleware, quality of service, industrial networks and real-time cloud computing. Prerequisite: CSE 422S.
Credit 3 units. EN: BME T, TU

E81 CSE 521S Wireless Sensor Networks
Dense collections of smart sensors networked to form self-configuring pervasive computing systems provide a basis for a new computing paradigm that challenges many classical approaches to distributed computing. Naming, wireless networking protocols, data management and approaches to dependability, real-time, security and middleware services all fundamentally change when confronted with this new environment. Embedded sensor networks and pervasive computing are among the most exciting research areas with many open research questions. This class studies a large number of research papers that deal with various aspects of wireless sensor networks. Students perform a project on a real wireless sensor network composed of tiny devices each consisting of sensors, a radio transceiver and a microcontroller. Prerequisite: CSE 422S.
Credit 3 units. EN: BME T, TU

E81 CSE 522S Advanced Operating Systems
This course offers an in-depth hands-on exploration of core OS abstractions, mechanisms and policies, with an increasing focus on understanding and evaluating their behaviors and interactions. Readings, lecture material, studio exercises, and lab assignments are closely integrated in an active-learning environment in which students gain experience and proficiency writing, tracing, and evaluating user-space and kernel-space code. Topics include: inter-process communication, real-time systems, memory forensics, file-system forensics, timing forensics, process and thread forensics, hypervisor forensics, and managing internal or external causes of anomalous behavior. Prerequisite: CSE 422S.
Credit 3 units. EN: BME T, TU

E81 CSE 523S Systems Security
This course examines the intersection between computer design and information security. While performance and efficiency in digital systems have improved markedly in recent decades, computer security has worsened overall in this time frame. To understand why, we will explore the role that design choices play in the security characteristics of modern computer and network systems. Students will use and write software to illustrate mastery of the material. Projects will include identifying security vulnerabilities, exploiting vulnerabilities, and detecting and defending against exploits. Prerequisite: CSE 361S.
Credit 3 units. EN: BME T, TU

E81 CSE 530S Database Management Systems
A study of data models and the database management systems that support these data models. The design theory for databases is developed and various tools are utilized to apply the theory. General query languages are studied and techniques for query optimization are investigated. Integrity and security requirements are studied in the context of concurrent operations on a database, where the database may be distributed over one or more locations. The unique requirements for engineering design databases, image databases, and long transaction systems are analyzed. Prerequisite: CSE 247.
Credit 3 units.

E81 CSE 532S Advanced Multiparadigm Software Development
Intensive focus on advanced design and implementation of concurrent and distributed system software in C++. Topics covered include concurrency and synchronization features and software architecture patterns. Prerequisites: CSE 332S or graduate standing and strong familiarity with C++; and CSE 422S.
Credit 3 units. EN: BME T, TU

E81 CSE 538T Modeling and Performance Evaluation of Interconnected Computer Systems
Modern computing systems consist of multiple interconnected components, which all influence performance. The focus of this course is on developing modeling tools aimed at understanding how to design and provision such systems to meet certain performance or efficiency targets, and the trade-offs involved. The course covers Markov chains and their applications to simple queues, and proceeds to explore more complex systems including server farms and how to optimize their performance through scheduling and task assignment policies. The course includes a brief review of the necessary probability and mathematical concepts. Prerequisite: ESE 326.
Credit 3 units. EN: BME T, TU

E81 CSE 539S Concepts in Multicore Computing
Nowadays, the vast majority of computer systems are built using multicore processor chips. This fundamental shift in hardware design impacts all areas of computer science — one must write parallel programs in order to unlock the computational power provided by modern hardware. The goal of this course is to study concepts in multicore computing. We will examine the implications of the multicore hardware design, discuss challenges in writing high performance software, and study emerging technologies relevant to developing software for multicore systems. Topics include memory hierarchy, cache coherence protocol, memory models, scheduling, high-level parallel language models, concurrent programming (synchronization and concurrent data structures), algorithms for debugging parallel software, and performance analysis. Prerequisites: CSE 332S and CSE 361S.
Credit 3 units. EN: BME T, TU

E81 CSE 541T Advanced Algorithms
Provides a broad coverage of fundamental algorithm design techniques, with a focus on developing efficient algorithms for solving combinatorial and optimization problems. The topics covered include the review of greedy algorithms, dynamic programming, NP-completeness, approximation algorithms, the use of linear and convex programming for approximation, and online algorithms. Throughout this course, there is an emphasis on correctness proofs and the ability to apply the techniques taught to design efficient algorithms for problems from a wide variety of application areas. Prerequisite: CSE 347.
Credit 3 units. EN: BME T, TU

E81 CSE 543S Advanced Secure Software Engineering
The aim of this course is to provide students with broader and deeper knowledge as well as hands-on experience in understanding security techniques and methods needed in software development. Students complete an independent research project which will involve synthesizing multiple software
E81 CSE 543T Algorithms for Nonlinear Optimization
The course will provide an in-depth coverage of modern optimization problems for the numerical solution of multidimensional optimization problems. Unconstrained optimization techniques including gradient methods, Newton's methods, quasi-Newton methods, and conjugate methods will be introduced. The emphasis is on constrained optimization techniques: Lagrange theory, Lagrangian methods, penalty methods, sequential quadratic programming, primal-dual methods, duality theory, nondifferentiable dual methods, and decomposition methods. The course will also discuss applications in engineering systems and use of state-of-the-art computer codes. Special topics may include large-scale systems, parallel optimization, and convex optimization. Prerequisites: Calculus I and Math 309.
Credit 3 units.

E81 CSE 544T Special Topics in Computer Science Theory
The material for this course varies among offerings, but this course generally covers advanced or specialized topics in computer science theory.
Credit 3 units. EN: BME T, TU

E81 CSE 546T Computational Geometry
Computational geometry is the algorithmic study of problems that involve geometric shapes such as points, lines, and polygons. Such problems appear in computer graphics, vision, robotics, animation, visualization, molecular biology, and geographic information systems. This course covers data structures that are unique to geometric computing, such as convex hull, Voronoi diagram, Delaunay triangulation, arrangement, range searching, KD-trees, and segment trees. Also covered are algorithms for polygon triangulation, path planning, and the art gallery problem.
Prerequisite: CSE 347.
Credit 3 units.

E81 CSE 547T Introduction to Formal Languages and Automata
An introduction to the theory of computation, with emphasis on the relationship between formal models of computation and the computational problems solvable by those models. Specifically, this course covers finite automata and regular languages; Turing machines and computability; and basic measures of computational complexity and the corresponding complexity classes. Prerequisites: CSE 240 and CSE 247.
Credit 3 units.

E81 CSE 549T Theory of Parallel Systems
The course covers various aspects of parallel programming such as algorithms, schedulers and systems from a theoretical perspective. We will cover both classic and recent results in parallel computing. Topics include parallel algorithms and analysis in the work/span model, scheduling algorithms, external memory algorithms and their analysis, cache-coherence protocols, etc. The focus will be on design and analysis.
Prerequisite: CSE 247.
Credit 3 units. EN: BME T, TU

E81 CSE 554A Geometric Computing for Biomedicine
With the advance of imaging technologies deployed in medicine, engineering, and science, there is a rapidly increasing amount of spatial data sets (e.g., images, volumes, point clouds) that need to be processed, visualized, and analyzed. This course will focus on a number of geometry-related computing problems that are essential to the knowledge discovery process in various spatial-data–driven biomedical applications. These problems include visualization, segmentation, mesh construction and processing, and shape representation and analysis. The course consists of lectures that cover theories and algorithms as well as a series of hands-on programming projects using real-world data collected by various imaging techniques (e.g., CT, MRI, electron cryomicroscopy). Prerequisites: CSE 247 and CSE 332 (or proficiency in programming in C++, Java, or Python).
Credit 3 units. EN: BME T, TU

E81 CSE 555A Computational Photography
Computational Photography describes the convergence of computer graphics, computer vision, and the internet with photography. Its goal is to overcome the limitations of traditional photography using computational techniques to enhance the way we capture, manipulate and interact with visual media. In this course we study many interesting, recent image-based algorithms and implement them to the degree that is possible. Topics may include: cameras and image formation, human visual perception, image processing (filtering, pyramids), image blending and compositing, image retargeting, texture synthesis and transfer, image completion/inpainting, super-resolution, deblurring, denoising, image-based lighting and rendering, high dynamic range, depth and defocus, flash/no flash photography, coded aperture photography, single/multiview reconstruction, photo quality assessment, non photorealistic rendering, modeling and synthesis using internet data, and others. Prerequisites: CSE 452A, CSE 554A, or CSE 559A.
Credit 3 units. EN: BME T, TU

E81 CSE 556A Human-Computer Interaction Methods
An introduction to user centered design processes. The course covers a variety of HCI techniques for use at different stages in the software development cycle, including techniques that can be used with and without users. Students will gain experience using these techniques through in-class exercises and then apply them in greater depth through a semester long interface development project. Students who enroll in this course are expected to be comfortable with building user interfaces in at least one framework and be willing to learn whatever framework is most appropriate for their project. Over the course of the semester, students will be expected to present their interface evaluation results through written reports and in class presentations. Prerequisites: 3xxS or 4xxS.
Credit 3 units. EN: BME T, TU

E81 CSE 557A Advanced Visualization
We are in an era in which it is possible to have all of the world's information at our fingertips. However, the more information we can access, the more difficult it is to obtain a holistic view of the data or to determine what's important to make decisions. Computer-based visualization systems provide the opportunity to represent large or complex data visually to aid comprehension and cognition. In this course, we learn about the state of the art of visualization research and gain hands-on experience with the research pipeline. We also learn how to critique existing work and how to formulate and explore sound research questions. We
will cover advanced visualization topics, including user modeling, adaptation, personalization, perception, and visual analytics for non-experts. Prerequisites: CSE 457A or permission of the instructor.
Credit 3 units. EN: BME T, TU

**E81 CSE 559A Computer Vision**

This course introduces the fundamentals of designing computer vision systems that can "look at" images and videos and reason about the physical objects and scenes they represent. Topics include image restoration and enhancement, estimation of color, shape, geometry, and motion from images, and image segmentation, recognition, and classification. The focus of the course will be on the mathematical tools and intuition underlying algorithms for these tasks, models for the physics and geometry of image formation, and statistical and machine learning-based techniques for inference. Prerequisites: Math 309/ESE 318 and CSE 247.

Credit 3 units. EN: BME T, TU

**E81 CSE 560M 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 280M.

Credit 3 units. EN: BME T, TU

**E81 CSE 566S High Performance Computer Systems**

Many applications make substantial performance demands upon the computer systems upon which those applications are deployed. In this context, performance is frequently multidimensional, including resource efficiency, power, execution speed (which can be quantified via elapsed run time, data throughput, or latency), and so on. Modern computer platforms exploit parallelism and architectural diversity (e.g., co-processors such as graphics engines and/or reconfigurable logic) to achieve the desired performance goals. This course addresses the practical aspects of achieving high performance on modern computer platforms. This includes questions ranging from how the computing platform is designed to how are applications and algorithms expressed to exploit the platform's properties. Particular attention is given to the role of application development tools. Prerequisite: familiarity with software development in Linux preferred, graduate standing or permission of instructor.

Credit 3 units. EN: BME T, TU

**E81 CSE 567M 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 280M.

Credit 3 units. EN: BME T, TU

**E81 CSE 569S Advanced IoT, Real-Time, and Embedded Systems Security**

The aim of this course is to provide students with knowledge and hands-on experience in understanding the security techniques and methods needed for IoT, real-time, and embedded systems. Students complete an independent research project which will involve synthesizing multiple security techniques and applying them to an actual IoT, real-time, or embedded system or device.

Credit 3 units. EN: TU

**E81 CSE 570S Recent Advances in Networking**

This course covers the latest advances in networking. The topics include networking trends, data center network topologies, network coding and modulation, wireless local area networks, white spaces, IEEE 802.22 regional area networks, vehicular networks, Bluetooth and Bluetooth Smart, wireless personal area networks, cellular networks: 1G/2G/3G, LTE, LTE-Advanced, and 5G. The class project allows students to take a deep dive into a topic of choice in network security. Prerequisite: CSE 473S or equivalent.

Credit 3 units. EN: BME T, TU

**E81 CSE 571S Network Security**

This course covers principles and techniques in securing computer networks. Real world examples will be used to illustrate the rationales behind various security designs. There are three main components in the course, preliminary cryptography, network protocol security and network application security. Topics include IPSec, SSL/TLS, HTTPS, network fingerprinting, network malware, anonymous communication, and blockchain. The class project allows students to take a deep dive into a topic of choice in network security. Prerequisite: CSE 473S.

Credit 3 units. EN: BME T, TU

**E81 CSE 574S Wireless and Mobile Networking**

First course in wireless networking providing a comprehensive treatment of wireless data and telecommunication networks. Topics include recent trends in wireless and mobile networking, wireless coding and modulation, wireless signal propagation, IEEE 802.11a/b/g/n/ac wireless local area networks, 60 GHz millimeter wave gigabit wireless networks, vehicular wireless networks, white spaces, IEEE 802.22 regional area networks, Bluetooth and Bluetooth Smart, wireless personal area networks, wireless protocols for the "Internet of things," ZigBee, cellular networks: 1G/2G/3G, LTE, LTE-Advanced, and 5G. Prerequisites: CSE 473S or permission of the instructor.

Credit 3 units. EN: BME T, TU

**E81 CSE 581T Approximation Algorithms**

Numerous optimization problems are intractable to solve optimally. The intractability of a problem could come from the problem's computational complexity, for instance the problem is NP-Hard, or other computational barriers. To cope with the inability to find an optimal algorithm, one may desire an algorithm
that is guaranteed to return a solution that is comparable to the optimum. Such an algorithm is known as an approximation algorithm. Approximation algorithms are a robust way to cope with intractability, and they are widely used in practice or are used to guide the development of practical heuristics. The area of approximation algorithms has developed a vast theory, revealing the underlying structure of problems as well as their different levels of difficulty. The majority of this course will focus on fundamental results and widely applicable algorithmic and analysis techniques for approximation algorithms. Prerequisite: CSE 347.
Credit 3 units. EN: BME T, TU

E81 CSE 584A Algorithms for Biosequence Comparison
This course surveys algorithms for comparing and organizing discrete sequential data, especially nucleic acid and protein sequences. Emphasis is on tools to support research in massive biosequence databases and to perform fundamental comparison tasks such as DNA short-read alignment. These techniques are also of interest for more general string processing and for building and mining textual databases. Algorithms are presented rigorously, including proofs of correctness and running time, where feasible. Topics include classical string matching, suffix array string indices, space-efficient string indices, rapid inexact matching by covering (including BLAST and related tools), and alignment-free algorithms. Students complete written assignments and implement advanced comparison algorithms to address problems in bioinformatics. This course does not require a biology background. Prerequisites: CSE 347 or instructor permission.
Credit 3 units. EN: BME T, TU

E81 CSE 585T Sparse Modeling for Imaging and Vision
Sparse modeling is at the heart of modern imaging, vision, and machine learning. It is a fascinating new area of research that seeks to develop highly effective data models. The core idea in sparse modeling theory is a novel redundant transform, where the number of transform coefficients is larger compared to the original data dimension. Together with redundancy comes an opportunity of seeking the sparsest possible representation, or the one with the fewest non-zeros. This core idea leads to a series of beautiful theoretical and practical results with many applications such as regression, prediction, restoration, extrapolation, compression, detection, and recognition. In this course, we will explore sparse modeling by covering theoretical as well as algorithmic aspects with applications in computational imaging and computer vision. Prerequisites: ESE 318, Math 233, Math 309, and Math 429, or equivalents. Coding with MATLAB or Python.
Credit 3 units. EN: BME T, TU

E81 CSE 586A Analysis of Imaging Data
This course focuses on an in-depth study of advanced topics and interests in image data analysis. Students will learn about hardcore imaging techniques and gain the mathematical fundamentals needed to build their own models for effective problem solving. Topics of deformable image registration, numerical analysis, probabilistic modeling, data dimensionality reduction, and convolutional neural networks for image segmentation will be covered. The main focus might change from semester to semester. Prerequisites: Math 309, ESE 326, CSE 247.
Credit 3 units.

E81 CSE 587A Algorithms for Computational Biology
This course is a survey of algorithms and mathematical methods in biological sequence analysis (with a strong emphasis on probabilistic methods) and systems biology. Sequence analysis topics include introduction to probability, probabilistic inference in missing data problems, hidden Markov models (HMMs), profile HMMs, sequence alignment, and identification of transcription-factor binding sites. Systems biology topics include discovery of gene regulatory networks, quantitative modeling of gene regulatory networks, synthetic biology, and (in some years) quantitative modeling of metabolism. Prerequisite: CSE131 or CSE501N.
Credit 3 units. EN: TU

E81 CSE 591 Introduction to Graduate Study in CSE
Introduces students to the different areas of research conducted in the department. Provides an introduction to research skills, including literature review, problem formulation, presentation, and research ethics. Lecture and discussion are supplemented by exercises in the different research areas and in critical reading, idea generation, and proposal writing.
Credit 3 units.

E81 CSE 598 Master's Project
Students electing the project option for their master's degree perform their project work under this course. In order to successfully complete this course, students must defend their project before a three-person committee and present a 2-3 page extended abstract. Prerequisite: permission of adviser and submission of a research proposal form.
Credit variable, maximum 6 units.

E81 CSE 599 Master's Research
Students electing the thesis option for their master's degree perform their thesis research under this course. In order to successfully complete a master's thesis, students must enroll in 6 units of this course typically over the course of two consecutive semesters, produce a written thesis, and defend the thesis before a three-person committee. Prerequisite: permission of adviser and submission of a research proposal form.
Credit variable, maximum 6 units.

E81 CSE 637S Software Security
In this course, students will be introduced to the foundations of software security. They will be exploring different classes of software vulnerabilities, analyzing the fundamental problems behind these vulnerabilities, and studying the methods and techniques to discover, exploit, prevent and mitigate these vulnerabilities. Topics of interest include buffer overflow, integer overflow, type confusion, and use-after-free. Throughout the course, we will take a defense-in-depth mentality and see how systems can be protected. Students are expected to have a solid understanding of assembly language, C/C++, and operating systems. Prerequisite: CSE 361S.
Credit 3 units.

E81 CSE 659A Advances in Computer Vision
This course will describe advanced and modern algorithms for computer vision and pattern recognition applications. We will cover various techniques for modeling images and physical and semantic attribute maps, advanced algorithms for continuous and discrete optimization, and modern learning approaches
based on the use of deep convolutional neural networks. Prerequisite: CSE 559A or permission of instructor. Credit 3 units.

E81 CSE 699 Doctoral Research
Credit variable, maximum 9 units.

E81 CSE 7100 Research Seminar on Machine Learning
Research seminars examine publications, techniques, approaches and strategies within an area of computer science and engineering. Seminars are highly participational: Students are expected to take turns presenting material, to prepare for seminar by reading any required material, and to contribute to the group's discussions. The actual topics covered in a seminar will vary by semester and instructor. Interested students are encouraged to obtain a syllabus from the instructor's webpage or by contacting the instructor. Credit 1 unit.

E81 CSE 7200 Research Seminar on Robotics and Human-Computer Interaction
Research seminars examine publications, techniques, approaches and strategies within an area of computer science and engineering. Seminars are highly participational: Students are expected to take turns presenting material, to prepare for seminar by reading any required material, and to contribute to the group's discussions. The actual topics covered in a seminar will vary by semester and instructor. Interested students are encouraged to obtain a syllabus from the instructor's webpage or by contacting the instructor. Credit 1 unit.

E81 CSE 7300 Research Seminar on Software Systems
Research seminars examine publications, techniques, approaches and strategies within an area of computer science and engineering. Seminars are highly participational: Students are expected to take turns presenting material, to prepare for seminar by reading any required material, and to contribute to the group's discussions. The actual topics covered in a seminar will vary by semester and instructor. Interested students are encouraged to obtain a syllabus from the instructor's webpage or by contacting the instructor. Credit 1 unit.

E81 CSE 7400 Research Seminar on Algorithms and Theory
Research seminars examine publications, techniques, approaches and strategies within an area of computer science and engineering. Seminars are highly participational: Students are expected to take turns presenting material, to prepare for seminar by reading any required material, and to contribute to the group's discussions. The actual topics covered in a seminar will vary by semester and instructor. Interested students are encouraged to obtain a syllabus from the instructor's webpage or by contacting the instructor. Credit 1 unit.

E81 CSE 7500 Research Seminar on Graphics and Vision
Research seminars examine publications, techniques, approaches and strategies within an area of computer science and engineering. Seminars are highly participational: Students are expected to take turns presenting material, to prepare for seminar by reading any required material, and to contribute to the group's discussions. The actual topics covered in a seminar will vary by semester and instructor. Interested students are encouraged to obtain a syllabus from the instructor's webpage or by contacting the instructor. Credit 1 unit.

E81 CSE 7600 Research Seminar on Analog Computing
This seminar will focus on classic and recent papers on analog, stochastic and neuromorphic computing. Students will read, present, and discuss journal papers on analog techniques for implementing sensors and processors. Focus will be placed on fundamental advances and challenges of implementing analog processors. No prerequisites. Credit 1 unit.

E81 CSE 7700 Research Seminar on Networking and Communications
Research seminars examine publications, techniques, approaches and strategies within an area of computer science and engineering. Seminars are highly participational: Students are expected to take turns presenting material, to prepare for seminar by reading any required material, and to contribute to the group's discussions. The actual topics covered in a seminar will vary by semester and instructor. Interested students are encouraged to obtain a syllabus from the instructor's webpage or by contacting the instructor. Credit 1 unit.

E81 CSE 7800 Research Seminar on Computational Systems Biology
Research seminars examine publications, techniques, approaches and strategies within an area of computer science and engineering. Seminars are highly participational: Students are expected to take turns presenting material, to prepare for seminar by reading any required material, and to contribute to the group's discussions. The actual topics covered in a seminar will vary by semester and instructor. Interested students are encouraged to obtain a syllabus from the instructor's webpage or by contacting the instructor. Credit 1 unit.

E81 CSE 7900 Research Seminar on Parallel Computing
This seminar will focus on classic and recent papers on parallel computing. Students will read, present and discuss papers on parallel models, algorithms and architectures from top conferences and journals. Focus will be placed on fundamental advances and theoretical models and algorithms, rather than on implementation papers. No prerequisites. Credit 1 unit.

E81 CSE 801 Pedagogy
A student taking this course studies the fundamentals of teaching in the discipline of computer science and computer engineering. A student enrolled in this course staffs some other course taught by our department, serving as its primary instructor or co-instructor. That student receives frequent mentoring and feedback on preparation and delivery. This course is recommended especially for doctoral students who seek a career in computer science and engineering education. Credit 3 units.