Electrical & Systems Engineering

The Department of Electrical & Systems Engineering offers doctoral-level and master’s-level degrees in Electrical Engineering and in Systems Science & Mathematics. At the doctoral level, both the PhD and DSc degrees are available, which typically require four to five years of full-time study leading to an original research contribution. At the master’s level, the programs require 30 credit hours of study and have both a course option and a thesis option.

Research activity in the department is focused in the following four areas:

**Applied Physics**
- Nanophotonics
- Quantum optics
- Engineered materials
- Electrodynamics

**Devices & Circuits**
- Computer engineering
- Integrated circuits
- Radiofrequency circuits
- Sensors

**Systems Science**
- Optimization
- Applied mathematics
- Control
- Financial engineering

**Signals & Imaging**
- Computational imaging
- Signal processing
- Optical imaging
- Data sciences

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

Prospective PhD students with previous degrees in engineering who are interested in PhD studies and research in mathematics or statistics are encouraged to apply for PhD studies in Mathematics and Statistics. For more details, visit the Graduate Programs in Mathematics and Statistics (http://wumath.wustl.edu/graduate) webpage.

**Faculty**

**Chair**

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

**Endowed Professors**

Arye Nehorai
Eugene and Martha Lohman Professor of Electrical Engineering
PhD, Stanford University
Signal processing, imaging, biomedicine, communications

Joseph A. O’Sullivan
Samuel C. Sachs Professor of Electrical Engineering
Dean, UMSL/WUSTL Joint Undergraduate Engineering Program
PhD, Notre Dame University
Information theory, statistical signal processing, imaging science with applications in medicine and security, and recognition theory and systems

Lan Yang
Edward H. & Florence G. Skinner Professor of Engineering
PhD, California Institute of Technology
Nano/micro photonics, ultra high-quality optical microcavities, ultra-low-threshold microlasers, nano/micro fabrication, optical sensing, single nanoparticle detection, photonic molecules, photonic materials

**Professors**

Shantanu Chakrabartty
PhD, Johns Hopkins University
New frontiers in unconventional analog computing techniques using silicon and hybrid substrates, fundamental limits of energy efficiency, sensing and resolution by exploiting computational and adaptation primitives inherent in the physics of devices

Hiroaki Mukai
PhD, University of California, Berkeley
Theory and computational methods for optimization, optimal control, systems theory, electric power system operations, differential games
Heinz Schaettler (https://engineering.wustl.edu/Profiles/Pages/Heinz-Schaettler.aspx)
PhD, Rutgers University
Optimal control, nonlinear systems, mathematical models in biomedicine

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

Robert E. Morley Jr. (https://engineering.wustl.edu/Profiles/Pages/Robert-Morley.aspx)
DSc, Washington University
Computer and communication systems, VLSI design, digital signal processing

Assistant Professors
ShiNung Ching (https://engineering.wustl.edu/Profiles/Pages/ShiNung-Ching.aspx)
Das Family Distinguished Career Development Assistant Professor
PhD, University of Michigan
Systems and control in neural medicine, nonlinear and constrained control, physiologic network dynamics, stochastic control

Zachary Feinstein (https://engineering.wustl.edu/Profiles/Pages/Zachary-Feinstein.aspx)
PhD, Princeton University
Financial engineering, operations research, variational analysis

Ulubek Kamilov (https://ese.wustl.edu/faculty/Pages/default.aspx?bio=120)
PhD, Ecole Polytechnique Federale de Lausanne, Switzerland
Computational imaging, signal processing, biomedical imaging

Matthew D. Lew (https://engineering.wustl.edu/Profiles/Pages/Matthew-Lew.aspx)
PhD, Stanford University
Microscopy, biophotonics, computational imaging, nanophotonics

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

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

Shen Zeng (https://ese.wustl.edu/faculty/Pages/default.aspx?bio=121)
PhD, University of Stuttgart
Systems and control theory, data-based analysis and control of complex dynamical systems, inverse problems, biomedical applications

Xuan "Silvia" Zhang (https://engineering.wustl.edu/Profiles/Pages/Xuan-%28Silvia%29-Zhang.aspx)
PhD, Cornell University
Robotics, cyber-physical systems, hardware security, ubiquitous computing, embedded systems, computer architecture, VLSI, electronic design automation, control optimization, and biomedical devices and instrumentation

Senior Professors
I. Norman Katz
PhD, Massachusetts Institute of Technology
Numerical analysis, differential equations, finite element methods, locational equilibrium problems, algorithms for parallel computations

Paul S. Min
PhD, University of Michigan
Routing and control of telecommunication networks, fault tolerance and reliability, software systems, network management

William F. Pickard
PhD, Harvard University
Biological transport, electobiology, energy engineering

Daniel L. Rode
PhD, Case Western Reserve University
Optoelectronics and fiber optics, semiconductor materials, light-emitting diodes (LEDs) and lasers, semiconductor processing, electronics

Ervin Y. Rodin
PhD, University of Texas at Austin
Optimization, differential games, artificial intelligence, mathematical modeling

Barbara A. Shrauner
PhD, Harvard University (Radcliffe)
Plasma processing, semiconductor transport, symmetries of nonlinear differential equations

Donald L. Snyder
PhD, Massachusetts Institute of Technology
Communication theory, random process theory, signal processing, biomedical engineering, image processing, radar
Barry E. Spielman  
PhD, Syracuse University  
High-frequency/high-speed devices, RF & MW integrated circuits, computational electromagnetics

Tzyh Jong Tarn  
DSc, Washington University  
Quantum mechanical systems, bilinear and nonlinear systems, robotics and automation, life science automation

Professors of Practice

Dedric Carter  
PhD, Nova Southeastern University  
MBA, MIT Sloan School of Management

Dennis Mell  
MS, University of Missouri-Rolla

Ed Richter  
MS, Washington University

Jason Trobaugh  
DSc, Washington University

Senior Lecturer

Martha Hasting  
PhD, Saint Louis University

Lecturers

Randall Brown  
PhD, Washington University

Randall Hoven  
MS, Johns Hopkins University

Vladimir Kurenok  
PhD, Belarus State University (Minsk, Belarus)

Tsitsi Madziwa-Nussinov  
PhD, University of California, Los Angeles

Jinsong Zhang  
PhD, University of Miami

Research Assistant Professors

Scott Marrus  
MD, PhD, Washington University School of Medicine  
Cardiac electrophysiology

Professors Emeriti

William M. Boothby  
PhD, University of Michigan  
Differential geometry and Lie groups, mathematical system theory

Lloyd R. Brown  
DSc, Washington University  
Automatic control, electronic instrumentation

David L. Elliott  
PhD, University of California, Los Angeles  
Mathematical theory of systems, nonlinear difference, differential equations

Robert O. Gregory  
DSc, Washington University  
Electronic instrumentation, microwave theory, circuit design

Degree Requirements

Please refer to the following sections for information about:

- Doctoral Degrees (p. 3)
- MS in Electrical Engineering (MSEE) (p. 4)
- MS in Systems Science & Mathematics (MSSSM) (p. 5)
- MS in Data Analytics and Statistics (MSDAS) (p. 5)
- Master of Control Engineering (MCEng) (p. 5)
- Master of Engineering in Robotics (MEngR) (p. 6)
- Imaging Science & Engineering (IS&E) (p. 7)

Doctoral Degrees

Students pursuing the Doctor of Philosophy (PhD) or Doctor of Science (DSc) degrees in Electrical Engineering or Systems Science & Mathematics must complete a minimum of 72 credit hours of post-baccalaureate study consistent with the residency and other applicable requirements of Washington University in St. Louis and the Graduate School. These 72 units must consist of at least 36 units of course work and at least 24 units of research, and may include work done to satisfy the requirements of a master's degree in a related discipline. Up to 24 units for the PhD and 30 units for the DSc may be transferred to Washington University in St. Louis from another institution.

Following are stages to the completion of the requirements for a doctoral degree in the Department of Electrical & Systems Engineering. Each candidate for the degree must:

- Complete at least 36 hours of post-baccalaureate course work
- Pass a written qualifying examination, to be taken before the second academic year of the program
- Pass an oral preliminary research examination, to be completed within two years of passing the written qualifying examination, and at least one year prior to completion of the dissertation
- Satisfy the general residency requirement for the Graduate School (PhD) or the School of Engineering & Applied Science (DSc)
- Satisfy the general teaching requirement for PhD degrees offered by the Graduate School; no teaching requirement for the DSc
- Write a doctoral dissertation that describes the results of original and creative research in a specialization within electrical engineering or systems science and mathematics
• Pass a final oral examination in defense of the dissertation research
• Take ESE 590 Electrical & Systems Engineering Graduate Seminar each semester

The doctoral degree should ordinarily take no more than five years to complete, for students who enter the program with a baccalaureate degree. While individual circumstances will vary, the typical timeline will be as follows:
• Year 1: Course work and written qualifying examination
• Year 2: Course work, preliminary research, research advisory committee selection
• Year 3: Course work and preliminary research examination
• Year 4: Research
• Year 5: Research, completion of dissertation, and final oral examination

Students who enter the program with a master's degree may be able to shorten this timeline by one year or more.

Master's Degrees

Either a thesis option or a course option may be selected for the master's degree programs shown below. The special requirements for these options are as follows:

Course Option

This option is intended for those employed in local industry who wish to pursue a graduate degree on a part-time basis, or for full-time students who do not seek careers in research. Students must have a cumulative grade point average of at least 3.2 out of a possible 4.0 over all courses applied toward the degree. Under the course option, students may not take ESE 599 Master's Research, and with faculty permission may take up to 3 units of ESE 500 Independent Study for the MSEE program and up to 6 units of ESE 500 for the MSSSM, MSDAS, MCEng and MEngR programs.

Thesis Option

This option is intended for those pursuing full-time study and engaged in research projects. Candidates for this degree must complete a minimum of 24 credit hours of course instruction and six (6) credit hours of thesis research (ESE 599). These six (6) credit hours of thesis research can be counted as part of the 15 graduate-level electrical engineering credit hours for the MSEE program and as part of electives for the MSSSM, MSDAS, MCEng and MEngR programs. The student must write a master's thesis and defend it in an oral examination.

MS in Electrical Engineering

Students pursuing the degree Master of Science in Electrical Engineering (MSEE) must complete a minimum of 30 credit hours of study consistent with the residency and other applicable requirements of Washington University and the School of Engineering & Applied Science, and subject to the following departmental requirements.

• A minimum of 15 of these credit hours must be at the graduate level in electrical engineering subjects taught by the Department of Electrical & Systems Engineering (ESE). The list of courses that may be used to satisfy the 15-credit graduate-level course requirement is:
  ESE 513 Convex Optimization and Duality Theory
  ESE 415 Optimization
  ESE 516 Optimization in Function Space
  ESE 519 Convex Optimization
  ESE 520-529 Applied probability category
  ESE 530-539 Applied physics and electronics category
  ESE 540-549 Control category
  ESE 550-559 Systems category
  ESE 560-569 Computer engineering category
  ESE 570-579 Communications category
  ESE 580-589 Signal and image processing category
  ESE 599 Master's Research (thesis option only, max 6 units)

• The remaining courses in the program may be selected from senior- or graduate-level courses in ESE or elsewhere in the university. Courses outside of ESE must be in technical subjects relevant to electrical engineering and require the department's approval. Only one CSE graduate course which does not carry CSE graduate credit may be used to satisfy the MSEE degree. Undergraduate Laboratory courses may not be used to satisfy this requirement.
  • A maximum of one 500-level cross-listed ESE course, whose home department is outside of ESE, may be applied toward the 15-credit graduate-level requirement.
  • At least 15 units of the 30 total units applied toward the MSEE degree must be in ESE courses which, if cross-listed, have ESE as the home department.
  • A maximum of 6 credits may be transferred from another institution and applied toward the MSEE degree. Regardless of subject or level, all transfer courses are treated as electives and do not count toward the requirement of 15 credit hours of graduate-level electrical engineering courses.
  • ESE 590 Electrical & Systems Engineering Graduate Seminar must be taken each semester. Master of Science students must attend at least three seminars per semester.
  • The degree program must be consistent with the residency and other applicable requirements of Washington University and the School of Engineering & Applied Science.
  • Students must have a cumulative grade point average of at least 3.2 out of a possible 4.0 over all courses applied toward the degree.
### MS in Systems Science & Mathematics

The Master of Science in Systems Science & Mathematics (MSSSM) is an academic master's degree designed mainly for both full-time and part-time students interested in proceeding to the departmental full-time doctoral program and/or an industrial career.

- The MS degree requires 30 units, which may include optionally 6 units for thesis or independent study.
- Required courses (15 units) for the MS degree include:

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESE 551</td>
<td>Linear Dynamic Systems I</td>
<td>3</td>
</tr>
<tr>
<td>ESE 553</td>
<td>Nonlinear Dynamic Systems</td>
<td>3</td>
</tr>
<tr>
<td>ESE 520</td>
<td>Probability and Stochastic Processes</td>
<td>3</td>
</tr>
<tr>
<td>ESE 415</td>
<td>Optimization</td>
<td>3</td>
</tr>
</tbody>
</table>

and one chosen from the following courses:

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESE 524</td>
<td>Detection and Estimation Theory</td>
<td>3</td>
</tr>
<tr>
<td>or ESE 544</td>
<td>Optimization and Optimal Control</td>
<td></td>
</tr>
<tr>
<td>or ESE 545</td>
<td>Stochastic Control</td>
<td></td>
</tr>
<tr>
<td>or ESE 557</td>
<td>Hybrid Dynamic Systems</td>
<td></td>
</tr>
</tbody>
</table>

Total Units: 15

1. ESE 516 may be substituted for ESE 415.

- The remaining courses in the program may be selected from senior- or graduate-level courses in Electrical & Systems Engineering or elsewhere in the university. Courses outside of Electrical & Systems Engineering must be in technical subjects relevant to systems science and mathematics and require the department's approval.
- ESE 590 Electrical & Systems Engineering Graduate Seminar must be taken each semester. Master of Science students must attend at least three seminars per semester.
- The degree program must be consistent with the residency and other applicable requirements of Washington University and the School of Engineering & Applied Science.
- Students must have a cumulative grade point average of at least 3.2 out of a possible 4.0 over all courses applied toward the degree.

### MS in Data Analytics and Statistics

The MS in Data Analytics and Statistics (MSDAS) is an academic master's degree designed for students interested in learning statistical techniques necessary to make informed decisions based on data analysis.

- The MSDAS degree requires 30 units, which may include optionally 6 units for thesis.
- Required courses (15 units) for the MS degree include:

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESE 520</td>
<td>Probability and Stochastic Processes</td>
<td>3</td>
</tr>
<tr>
<td>or Math 493</td>
<td>Probability</td>
<td></td>
</tr>
<tr>
<td>ESE 524</td>
<td>Detection and Estimation Theory</td>
<td>3</td>
</tr>
<tr>
<td>Math 494</td>
<td>Mathematical Statistics</td>
<td>3</td>
</tr>
<tr>
<td>CSE 514A</td>
<td>Data Mining</td>
<td>3</td>
</tr>
<tr>
<td>or CSE 517A</td>
<td>Machine Learning</td>
<td></td>
</tr>
<tr>
<td>or CSE 530S</td>
<td>Database Management Systems</td>
<td></td>
</tr>
<tr>
<td>ESE 415</td>
<td>Optimization</td>
<td>3</td>
</tr>
<tr>
<td>or ESE 516</td>
<td>Optimization in Function Space</td>
<td></td>
</tr>
<tr>
<td>or ESE 518</td>
<td>Optimization Methods in Control</td>
<td></td>
</tr>
</tbody>
</table>

Total Units: 15

- The remaining courses in the program may be selected from senior- or graduate-level courses in ESE or elsewhere in the university. Courses must be in technical subjects relevant to statistics, optimization, computation, or applications of data analysis and require the department's approval.
- Program tracks in Statistics; Optimization and Decision Theory; Computing are available.
- The degree program must be consistent with the residency and other applicable requirements of Washington University and the School of Engineering & Applied Science.
- Students must have a cumulative grade point average of at least 3.2 out of a possible 4.0 over all courses applied toward the degree.

### Master of Control Engineering

The Master of Control Engineering (MCEng) degree is a terminal professional degree designed for students interested in an industrial career.

- The MCEng degree requires 30 units, which may include optionally 6 units for thesis.
- Required courses (15 units) for the MCEng degree include:

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESE 441</td>
<td>Control Systems</td>
<td>3</td>
</tr>
<tr>
<td>ESE 543</td>
<td>Control Systems Design by State</td>
<td>3</td>
</tr>
<tr>
<td>or ESE 425</td>
<td>Random Processes and Kalman Filtering</td>
<td></td>
</tr>
<tr>
<td>or ESE 551</td>
<td>Linear Dynamic Systems I</td>
<td></td>
</tr>
<tr>
<td>or ESE 552</td>
<td>Linear Dynamic Systems II</td>
<td></td>
</tr>
<tr>
<td>or ESE 553</td>
<td>Nonlinear Dynamic Systems</td>
<td></td>
</tr>
<tr>
<td>or ESE 547</td>
<td>Robust and Adaptive Control</td>
<td></td>
</tr>
</tbody>
</table>

and at least two of the following six courses:

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESE 415</td>
<td>Optimization</td>
<td>3</td>
</tr>
</tbody>
</table>
• Elective Courses (15 units): The 15 units of electives should be courses of a technical nature at the senior and graduate levels approved by the program director.

• 6 units may be transferred from another school as electives provided that the courses were not needed for the student's bachelor's degree.

• ESE 590 Electrical & Systems Engineering Graduate Seminar must be taken each semester.

• The degree program must be consistent with the residency and other applicable requirements of Washington University and the School of Engineering & Applied Science.

• Students must have a cumulative grade point average of at least 3.2 out of a possible 4.0 over all courses applied toward the degree.

Master of Engineering in Robotics

The principal goal of the Master of Engineering in Robotics (MEngR) degree program is to prepare individuals for professional practice in robotics engineering by leveraging the technical skills developed in an undergraduate engineering or physical science program. It is designed to be completed in 1.5 years, but it can be completed over a longer time period on a part-time basis. In order to finish in 1.5 years, students should take three courses (9 units) each in fall and spring semesters and four courses (12 units) in the second fall semester. For this program, the supervised project (6 units) is optional.

- The degree requires 30 units. The courses must be 400-level or higher and they must include at least 15 units of 500-level courses.

- Students must have a cumulative grade point average of at least 3.2 out of a possible 4.0 over all courses applied toward the degree.

- Required courses (12 units) for the MEngR degree include:

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESE 446</td>
<td>Robotics: Dynamics and Control</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>(Spring)</td>
<td></td>
</tr>
<tr>
<td>ESE 447</td>
<td>Robotics Laboratory (Fall, Spring)</td>
<td>3</td>
</tr>
<tr>
<td>ESE 551</td>
<td>Linear Dynamic Systems I (Fall)</td>
<td>3</td>
</tr>
<tr>
<td>CSE 511A</td>
<td>Introduction to Artificial Intelligence</td>
<td>3</td>
</tr>
<tr>
<td>or CSE 517A</td>
<td>Machine Learning</td>
<td></td>
</tr>
<tr>
<td>ESE 590</td>
<td>Electrical &amp; Systems Engineering Graduate Seminar (must be taken each semester)</td>
<td>0</td>
</tr>
</tbody>
</table>

  Total Units 12

- Elective Courses (18 units): At least one elective course must be selected from each of the following three groups. Other courses may be selected as electives with the approval of the program director.

  Optimization and Simulation Group

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESE 403</td>
<td>Operations Research (Fall)</td>
<td>3</td>
</tr>
<tr>
<td>ESE 407</td>
<td>Analysis and Simulation of Discrete Event Systems (Spring)</td>
<td>3</td>
</tr>
<tr>
<td>ESE 415</td>
<td>Optimization (Spring)</td>
<td>3</td>
</tr>
</tbody>
</table>

Control Engineering Group

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESE 441</td>
<td>Control Systems (Fall)</td>
<td>3</td>
</tr>
<tr>
<td>MEMS 4301</td>
<td>Modeling, Simulation and Control (Spring)</td>
<td></td>
</tr>
<tr>
<td>ESE 444</td>
<td>Sensors and Actuators (Fall)</td>
<td>3</td>
</tr>
<tr>
<td>ESE 425</td>
<td>Random Processes and Kalman Filtering (Fall)</td>
<td>3</td>
</tr>
<tr>
<td>ESE 543</td>
<td>Control Systems Design by State Space Methods (Fall)</td>
<td>3</td>
</tr>
<tr>
<td>ESE 552</td>
<td>Linear Dynamic Systems II (Spring)</td>
<td>3</td>
</tr>
<tr>
<td>ESE 553</td>
<td>Nonlinear Dynamic Systems (Spring)</td>
<td>3</td>
</tr>
</tbody>
</table>

Computer Science Group

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSE 511A</td>
<td>Introduction to Artificial Intelligence</td>
<td>3</td>
</tr>
<tr>
<td>CSE 517A</td>
<td>Machine Learning</td>
<td>3</td>
</tr>
<tr>
<td>CSE 520S</td>
<td>Real-Time Systems (Fall)</td>
<td>3</td>
</tr>
<tr>
<td>CSE 521S</td>
<td>Wireless Sensor Networks</td>
<td>3</td>
</tr>
<tr>
<td>CSE 546T</td>
<td>Computational Geometry</td>
<td>3</td>
</tr>
<tr>
<td>CSE 553S</td>
<td>Advanced Mobile Robotics (Spring)</td>
<td>3</td>
</tr>
<tr>
<td>CSE 556A</td>
<td>Human-Computer Interaction Methods (Fall)</td>
<td>3</td>
</tr>
<tr>
<td>CSE 568M</td>
<td>Imaging Sensors (Spring)</td>
<td>3</td>
</tr>
<tr>
<td>CSE 559A</td>
<td>Computer Vision (Spring)</td>
<td>3</td>
</tr>
</tbody>
</table>

- Project Course: The MEngR program may include up to 6 units of project in the form of Independent Study as part of elective courses. The independent study could be in the form of a practicum or a special project and it requires approval from the program director.

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESE 500</td>
<td>Independent Study (Fall, Spring and Summer)</td>
<td>var.</td>
</tr>
<tr>
<td>CSE 500</td>
<td>Independent Study (Fall, Spring and Summer)</td>
<td>var.</td>
</tr>
<tr>
<td>MEMS 500</td>
<td>Independent Study (Fall, Spring and Summer)</td>
<td>var.</td>
</tr>
</tbody>
</table>

Preparation for the MEngR Program

The required courses assume the following foundations in mechanical engineering and materials science, electrical engineering, systems engineering, and computer science.
Although they do not count toward the degree program, they are recommended for those students who lack these foundations.

- MEMS 255 Engineering Mechanics II (mechanical engineering and materials science foundation, fall and spring)
- ESE 351 Signals and Systems (electrical and systems engineering foundation, fall and spring)
- CSE 501N Programming Concepts and Practice (computer science foundation, fall)

**Certificate in Imaging Science and Engineering**

Washington University has been a leader in imaging science research for over four decades, with many new medical imaging modalities, advanced applications in planetary science, and fundamental theory having been developed here. The Imaging Sciences Pathway in the Division of Biology and Biological Sciences in Arts & Sciences is jointly administered with the School of Engineering & Applied Science, with students pursuing degrees in departments across the university. The Imaging Science and Engineering (IS&E) certificate program complements the Imaging Sciences Pathway for students in the departments of Electrical & Systems Engineering, Computer Science & Engineering, Biomedical Engineering, and Physics. Upon completion of both the graduate degree sought and the requirements of the program, the student’s transcript will include the certificate. Each department has its own requirements, but all include the Imaging Science and Engineering Seminar. The program is flexible, so students are encouraged to appeal to the program director to identify individualized programs.

The Imaging Science and Engineering certificate program is built on the strengths in imaging science throughout the university; this multidisciplinary program is constructed to expose students to the breadth of imaging research activities at Washington University. There has been an explosion of both increased bandwidth of existing imaging systems and new sensing modalities. The increase in bandwidth from sensors drives innovations in computing, image reconstruction, and image understanding. New sensing modalities present unique opportunities for young researchers to make fundamental contributions.

Medical imaging continues to comprise the largest set of applications at Washington University. The resolution of modern whole-body imaging sensors has revolutionized medicine. The development of new portable imaging modalities broadens the impact by lowering cost. Imaging science includes understanding of the underlying physical, biological, and chemical processes that yield signals of interest. Microscopes, visible/infrared cameras, magnetic resonance, x-ray, ultrasound, and nuclear sensors provide the data used for imaging or inferring underlying processes. Imaging supports clinical diagnosis, radiation oncology, molecular and neural imaging.

Imaging supports advances in earth and planetary science, enabling discovery from rovers on Mars, characterization of surface properties from satellites, and inferring internal phenomena in planetary objects. Modern understanding of materials science is driven in part by new imaging methods. New imaging systems for plant science seek better characterization of their biological systems.

Data rates from imaging systems demand efficient processing, manipulation and representation. In modern imaging systems, computing and sensing often must be jointly optimized. Inference is typically based on searching for meaningful patterns in the data, along with the relative contributions of those patterns.

For more information, please refer to either the Department of Electrical & Systems Engineering website (http://ese.wustl.edu) or contact the department directly.

**Entering and Completing the Program**

Graduate students in participating departments may apply for admission to the IS&E program. Admission requires graduate standing in a participating department, a demonstrated interest in aspects of imaging, and approval of the program director.

Upon being awarded a graduate degree by their home department and by completing certain requirements of the program, students are awarded a certificate indicating their successful participation in the IS&E program. The requirements for receiving a certificate are: acceptance into the IS&E program, completion of four imaging courses approved by the program director, completion of requirements for a graduate degree in the student’s home department, and participation in the Imaging Science seminar required for all students in the IS&E program.

Seminars by faculty in imaging science, others at Washington University, and experts from outside the university convey new developments and directions in the field of imaging science and its applications. These seminars also provide the opportunity for interactions among those involved in the program.

**Courses of Instruction**

Fundamentals underlying imaging science and engineering and the application of these fundamentals to contemporary problems of importance form the theme of the program. Relevant courses come from across the university. The program is flexible, allowing students, in consultation with their advisers and the program director, to design a program that is best for them. Below are representative courses that students in the program take.

**Courses in the Imaging Sciences Pathway in the Division of Biology and Biological Sciences**

- ESE 596 Seminar in Imaging Science and Engineering/CSE 596/BME 506/Physics 596 *(required)*
- BME 530A Molecular Cell Biology for Engineers
- ESE 589 Biological Imaging Technology/BME 589
• Biol 5068 Fundamentals of Molecular Cell Biology
• Biol 5146 Principles and Applications of Biological Imaging
• Biol 5147 Contrast Agents for Biological Imaging/Chem 5147

Courses in Electrical & Systems Engineering
• ESE 438 Applied Optics
• ESE 520 Probability and Stochastic Processes
• ESE 524 Detection and Estimation Theory
• ESE 582 Fundamentals and Applications of Modern Optical Imaging
• ESE 585 Optical Imaging
• ESE 586A Tomographic Imaging
• ESE 587 Ultrasonic Imaging Systems
• ESE 588 Quantitative Image Processing
• ESE 589 Biological Imaging Technology
• ESE 591 Special Topics: Biomedical Topics I: Principles
• ESE 592 Special Topics: Biomedical Topics II: Imaging
• ESE 596 Seminar in Imaging Science and Engineering (required)
• CSE 554A Geometric Computing for Biomedicine
• CSE 559A Computer Vision
• CSE 568M Imaging Sensors

Courses in Biomedical Imaging
• BME 502 Cardiovascular MRI — Physics to Clinical Application
• BME 503A Cell and Organ Systems Biology
• BME 504 Light Microscopy and Optical Imaging
• BME 506 Seminar in Imaging Science and Engineering (required)
• BME 530A Molecular Cell Biology for Engineers
• BME 589 Biological Imaging Technology
• BME 5907 Advanced Concepts in Image Science
• BME 591 Biomedical Optics I: Principles
• BME 592 Special Topics: Biomedical Topics II: Imaging
• BME 593 Computational Methods for Inverse Problems

Courses in Physics
• Physics 534 Magnetic Resonance
• Physics 589 Selected Topics in Physics I
• Physics 590 Selected Topics in Physics II
• Seminar-Physics of Ultrasonic Imaging in Cardiovascular Medicine

Courses in Computer Science & Engineering
• CSE 517A Machine Learning
• CSE 546T Computational Geometry
• CSE 552A Advanced Computer Graphics

Other Courses
• Psych 4450 Functional Neuroimaging Methods

Courses
Visit online course listings to view semester offerings for E35 ESE (https://courses.wustl.edu/CourseInfo.aspx?sch=E&dept=E35&crslvl=5-8).

E35 ESE 500 Independent Study
Opportunities to acquire experience outside the classroom setting and to work closely with individual members of the faculty. A final report must be submitted to the department. Prerequisite: Students must have the ESE Research/Independent Study Registration Form (PDF) (https://ese.wustl.edu/research/areas/Documents/Independent%20Study%20Form_1.pdf) approved by the department. Credit variable, maximum 3 units.

E35 ESE 501 Mathematics of Modern Engineering I
Matrix algebra: systems of linear equations, vector spaces, linear independence and orthogonality in vector spaces, eigenvectors and eigenvalues; vector calculus: gradient, divergence, curl, line and surface integrals, theorems of Green, Stokes, and Gauss; Elements of Fourier analysis and its applications to solving some classical partial differential equations, heat, wave, and Laplace equation. Prerequisites: ESE 318 and ESE 319 or equivalent or consent of instructor. Credit 3 units.

E35 ESE 502 Mathematics of Modern Engineering II
Fourier series and Fourier integral transforms and their applications to solving some partial differential equations, heat and wave equations; complex analysis and its applications to solving real-valued problems: analytic functions and their role, Laurent series representation, complex-valued line integrals and their evaluation including the residual integration theory, conformal mappings and their applications. Prerequisites: ESE 318 and ESE 319 or ESE 317 or equivalent, or consent of instructor. This course will not count toward the ESE doctoral program. Credit 3 units.

E35 ESE 512 Advanced Numerical Analysis
Special topics chosen from numerical solution of partial differential equations, uniform and least-squares approximation spline approximation, Galerkin methods and finite element approximation, functional analysis applied to numerical mathematics, and other topics of interest. Prerequisite: ESE 511 or consent of instructor. Credit 3 units.

E35 ESE 513 Convex Optimization and Duality Theory
Graduate introduction to convex optimization with emphasis on convex analysis and duality theory. Topics include: convex sets, convex functions, convex cones, convex conjugates, Fenchel-Moreau theorem, convex duality and biconjugation, directional derivatives, subgradients and subdifferentials, optimality conditions, ordered vector spaces, Hahn-Banach theorem.
extension and separation theorems, minimax theorems, and vector and set optimization. Prerequisites: ESE 415, Math 4111. Credit 3 units.

E35 ESE 514 Calculus of Variations
Introduction to the theory and applications of the calculus of variations. Theory of functionals; variational problems for an unknown function; Euler's equation; variable end-point problems; variational problems with subsidiary conditions; sufficient conditions for extrema: applications to optimum control and/or to other fields. A term project is required. Prerequisites: ESE 318 and 319 or ESE 317 or equivalent. Credit 3 units.

E35 ESE 516 Optimization in Function Space

E35 ESE 517 Partial Differential Equations
Linear and nonlinear first order equations. Characteristics. Classification of equations. Theory of the potential linear and nonlinear diffusion theory. Linear and nonlinear wave equations. Initial and boundary value problems. Transform methods. Integral equations in boundary value problems. Prerequisites: ESE 318 and 319 or equivalent or consent of instructor. Credit 3 units. EN: TU

E35 ESE 518 Optimization Methods in Control
The course is divided in two parts: convex optimization and optimal control. In the first part we cover applications of Linear Matrix Inequalities and Semi-Definite Programming to control and estimation problems. We also cover Multiparametric Linear Programming and its application to the Model Predictive Control and Estimation of linear systems. In the second part we cover numerical methods to solve optimal control problems, numerical methods to solve them, and their optimality conditions. We apply these results to the Model Predictive Control and Estimation of nonlinear systems. Prerequisites: ESE 551, and ESE 415 or equivalent. Credit 3 units. EN: TU

E35 ESE 519 Convex Optimization

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

E35 ESE 521 Random Variables and Stochastic Processes I
Mathematical foundations of probability theory, including constructions of measures, Lebesgue-measure, Lebesgue-integral, Banach space property of Lp, basic Hilbert-space theory, conditional expectation. Kolmogorov's theorems on existence and sample-path continuity of stochastic processes. An in-depth look at the Wiener process. Filtrations and stopping times. Markov processes and diffusions, including semigroup properties. Prerequisites: ESE 520 or equivalent. Math 411. Credit 3 units.

E35 ESE 523 Information Theory
Discrete source and channel model, definition of information rate and channel capacity, coding theorems for sources and channels, encoding and decoding of data for transmission over noisy channels. Corequisite: ESE 520. Credit 3 units. EN: TU

E35 ESE 524 Detection and Estimation Theory

E35 ESE 529 Special Topics in Information Theory and Applied Probability
Credit 3 units.

E35 ESE 531 Nano and Micro Photonics
This course focuses on fundamental theory, design, and applications of photonic materials and micro/nano photonic devices. It includes review and discussion of light-matter interactions in nano and micro scales, propagation of light in waveguides, nonlinear optical effect and optical properties of nano/micro structures, the device principles of waveguides, filters, photodetectors, modulators and lasers. Prerequisite: ESE 330. Credit 3 units. EN: TU

E35 ESE 532 Introduction to Nano-Photonic Devices
Introduction to photon transport in nano-photonic devices. This course focuses on the following topics: light and photons, statistical properties of photon sources, temporal and spatial correlations, light-matter interactions, optical nonlinearity, atoms
and quantum dots, single- and two-photon devices, optical devices, and applications of nano-photonic devices in quantum and classical computing and communication. Prerequisites: ESE 330 and Physics 217, or permission of instructor.
Credit 3 units. EN: TU

E35 ESE 534 Special Topics in Advanced Electrodynamics
This course covers advanced topics in electrodynamics. Topics include electromagnetic wave propagation (in free space, confined waveguides, or along engineered surfaces); electromagnetic wave scattering (off nano-particles or molecules); electromagnetic wave generation and detection (antenna and nano-antenna); inverse scattering problems; and numerical and approximate methods. Prerequisites: ESE 330, or Physics 421 and Physics 422.
Credit 3 units. EN: TU

E35 ESE 536 Introduction to Quantum Optics
This course covers the following topics: quantum mechanics for quantum optics, radiative transitions in atoms, lasers, photon statistics (photon counting, Sub-/Super-Poissonian photon statistics, bunching, anti-bunching, theory of photodetection, shot noise), entanglement, squeezed light, atom-photon interactions, cold atoms, atoms in cavities. If time permits, the following topics are selectively covered: quantum computing, quantum cryptography, and teleportation. Prerequisites: ESE 330 and Physics 217 or Physics 421.
Credit 3 units. EN: TU

E35 ESE 538 Advanced Electromagnetic Engineering
The course builds on undergraduate electromagnetics to systematically develop advanced concepts in electromagnetic theory for engineering applications. The following topics are covered: Maxwell's equations; fields and waves in materials; electromagnetic potentials and topics for circuits and systems; transmission-line essentials for digital electronics and for communications; guided wave principles for electronics and optoelectronics; principles of radiation and antennas; and numerical methods for computational electromagnetics.
Credit 3 units.

E35 ESE 543 Control Systems Design by State Space Methods
Advanced design and analysis of control systems by state-space methods: classical control review, Laplace transforms, review of linear algebra (vector space, change of basis, diagonal and Jordan forms), linear dynamic systems (modes, stability, controllability, state feedback, observability, observers, canonical forms, output feedback, separation principle and decoupling), nonlinear dynamic systems (stability, Lyapunov methods). Frequency domain analysis of multivariable control systems. State space control system design methods: state feedback, observer feedback, pole placement, linear optimal control. Design exercises with CAD (computer-aided design) packages for engineering problems. Prerequisite: ESE 351 and ESE 441, or permission of instructor.
Credit 3 units. EN: TU

E35 ESE 544 Optimization and Optimal Control
Constrained and unconstrained optimization theory. Continuous time as well as discrete-time optimal control theory. Time-optimal control, bang-bang controls and the structure of the reachable set for linear problems. Dynamic programming, the Pontryagin maximum principle, the Hamiltonian-Jacobi-Bellman equation and the Riccati partial differential equation. Existence of classical and viscosity solutions. Application to time optimal control, regulator problems, calculus of variations, optimal filtering and specific problems of engineering interest. Prerequisites: ESE 551, ESE 552.
Credit 3 units. EN: TU

E35 ESE 545 Stochastic Control
Credit 3 units. EN: TU

E35 ESE 546 Dynamics & Control in Neuroscience & Brain Medicine
This course provides an introduction to systems engineering approaches to modeling, analysis and control of neuronal dynamics at multiple scales. A central motivation is the manipulation of neuronal activity for both scientific and medical applications using emerging neurotechnology and pharmacology. Emphasis is placed on dynamical systems and control theory, including bifurcation and stability analysis of single neuron models and population mean-field models. Synchronization properties of neuronal networks are covered and methods for control of neuronal activity in both oscillatory and non-oscillatory dynamical regimes are developed. Statistical models for neuronal activity are also discussed. An overview of signal processing and data analysis methods for neuronal recording modalities is provided, toward the development of closed-loop neuronal control paradigms. The final evaluation is based on a project or research survey. Prerequisite(s): ESE 553 (or equivalent); ESE 520 (or equivalent); ESE 351 (or equivalent).
Credit 3 units. EN: TU

E35 ESE 547 Robust and Adaptive Control
Graduate-level control system design methods for multi-input multi-output systems. Linear optimal-based methods in robust control, nonlinear model reference adaptive control. These design methods are currently used in most industry control system design problems. These methods are designed, analyzed and simulated using MATLAB. Linear control theory (review), robustness theory (Mu Analysis), optimal control and the robust servomechanism, H-infinity optimal control, robust output feedback controls, Kalman filter theory and design, linear quadratic gaussian with loop transfer recovery, the Loop Transfer Recovery method of Lavretsky, Mu synthesis, Lyapunov theory (review), LaSalle extensions, Barbalat's Lemma, model reference adaptive control, artificial neural networks, online parameter estimation, convergence and persistence of excitation. Prerequisite: ESE 543 or ESE 551 or equivalent.
Credit 3 units. EN: TU

E35 ESE 549 Special Topics in Control
Credit 3 units.

E35 ESE 551 Linear Dynamic Systems I
Input-output and state-space description of linear dynamic systems. Solution of the state equations and the transition
matrix. Controllability, observability, realizations, pole-assignment, observers and decoupling of linear dynamic systems. Prerequisite: ESE 551. Credit 3 units. EN: TU

E35 ESE 552 Linear Dynamic Systems II

E35 ESE 553 Nonlinear Dynamic Systems
State space and functional analysis approaches to nonlinear systems. Questions of existence, uniqueness and stability; Lyapunov and frequency-domain criteria; w-limits and invariance, center manifold theory and applications to stability, steady-state response and singular perturbations. Poincare-Bendixon theory, the van der Pol oscillator, and the Hopf Bifurcation theorem. Prerequisite: ESE 551. Credit 3 units. EN: TU

E35 ESE 554 Advanced Nonlinear Dynamic Systems

E35 ESE 557 Hybrid Dynamic Systems
Theory and analysis of hybrid dynamic systems, which is the class of systems whose state is composed by continuous-valued and discrete-valued variables. Discrete-event systems models and language descriptions. Models for hybrid systems. Conditions for existence and uniqueness. Stability and verification of hybrid systems. Optimal control of hybrid systems. Applications to cyber-physical systems and robotics. Prerequisite: ESE 551. Credit 3 units. EN: TU

E35 ESE 555 Special Topics in Systems
Credit 3 units.

E35 ESE 560 Computer Systems Architecture I
An exploration of the central issues in computer architecture: instruction set design, addressing and register set design, control unit design, microprogramming, memory hierarchies (cache and main memories, mass storage, virtual memory), pipelining, and bus organization. The course emphasizes understanding the performance implications of design choices, using architecture modeling and evaluation using VHDL and/or instruction set simulation. Prerequisites: CSE 361S and CSE 260M. Same as E81 CSE 560M Credit 3 units. EN: TU

E35 ESE 561 Computer Systems Architecture II
Advanced techniques in computer system design. Selected topics from: processor design (multithreading, VLIW, data flow, chip-multiprocessors, application specific processors, vector units, large MIMD machines), memory systems (topics in locality, prefetching, reconfigurable and special-purpose memories), system specification and validation, and interconnection networks. Prerequisites: CSE 560M or permission of instructor. Same as E81 CSE 561M Credit 3 units. EN: TU

E35 ESE 562 Analog Integrated Circuits
This course focuses on fundamental and advanced topics in analog and mixed-signal VLSI techniques. The first part of the course covers graduate-level materials in the area of analog circuit synthesis and analysis. The second part of the course covers applications of the fundamental techniques for designing analog signal processors and data converters. Several practical aspects of mixed-signal design, simulation and testing are covered in this course. This is a project-oriented course, and it is expected that the students apply the concepts learned in the course to design, simulate and explore different circuit topologies. Prerequisites: CSE 260 and ESE 232. Credit 3 units.

E35 ESE 565 Acceleration of Algorithms in Reconfigurable Logic
Reconfigurable logic, in the form of Field-Programmable Gate Arrays (FPGAs), enables the deployment of custom hardware for individual applications. To exploit this capability, the application developer is required to specify the design at the register-transfer level. This course explores techniques for designing algorithms that are amenable to hardware acceleration as well as provides experience in actual implementation. Example applications are drawn from a variety of fields, such as networking, computational biology, etc. Prerequisites: basic digital logic (CSE 260M) and some experience with a hardware description language (e.g., VHDL or Verilog). Same as E81 CSE 565M Credit 3 units. EN: TU

E35 ESE 566A Modern System-on-Chip Design
The System-on-Chip (SoC) technology is at the core of most electronic systems: smart phones, wearable devices, autonomous robots, and cars, aerospace or medical electronics. In these SoCs, billions of transistors can be integrated on a single silicon chip, containing various components such as microprocessors, DSPs, hardware accelerators, memories, and I/O interfaces. Topics include SoC architectures, design tools and methods, as well as system-level tradeoffs between performance, power consumption, energy efficiency, reliability and programmability. Students gain an insight into the early stage of the SoC design process performing the tasks of developing functional specification, partition and map functions onto hardware and/or software, and evaluating and validating system performance. Assignments include hands-on design projects. Open to both graduate and senior undergraduate students. Prerequisite: ESE 461. Credit 3 units. EN: TU

E35 ESE 567 Computer Systems Analysis
A comprehensive course on performance analysis techniques. The topics include common mistakes, selection of techniques and metrics, summarizing measured data, comparing systems
using random data, simple linear regression models, other regression models, experimental designs, 2**k experimental designs, factorial designs with replication, fractional factorial designs, one factor experiments, two factor full factorial design w/o replications, two factor full factorial designs with replications, general full factorial designs, introduction to 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 131 and CSE 260M. 
Same as E81 CSE 567M
Credit 3 units. EN: TU

E35 ESE 569 Parallel Architectures and Algorithms
Several contemporary parallel computer architectures are reviewed and compared. The problems of process synchronization and load balancing in parallel systems are studied. Several selected applications problems are investigated and parallel algorithms for their solution are considered. Selected parallel algorithms are implemented in both a shared memory and distributed memory parallel programming environment. 
Prerequisites: graduate standing and knowledge of the C programming language. 
Same as E81 CSE 569M
Credit 3 units. EN: TU

E35 ESE 570 Coding Theory
Introduction to the algebra of finite fields. Linear block codes, cyclic codes, BCH and related codes for error detection and correction. Encoder and decoder circuits and algorithms. 
Spectral descriptions of codes and decoding algorithms. Code performances. 
Credit 3 units. EN: TU

E35 ESE 571 Transmission Systems and Multiplexing
Transmission and multiplexing systems are essential to providing efficient point-to-point communication over distance. This course introduces the principles underlying modern analog and digital transmission and multiplexing systems and covers a variety of system examples. 
Credit 3 units. EN: TU

E35 ESE 572 Signaling and Control in Communication Networks
The operation of modern communications networks is highly dependent on sophisticated control mechanisms that direct the flow of information through the network and oversee the allocation of resources to meet the communication demands of end users. This course covers the structure and operation of modern signaling systems and addresses the major design trade-offs that center on the competing demands of performance and service flexibility. Specific topics covered include protocols and algorithms for connection establishment and transformation, routing algorithms, overload and failure recovery and networking dimensioning. Case studies provide concrete examples and reveal the key design issues. Prerequisites: graduate standing and permission of instructor. 
Credit 3 units. EN: TU

E35 ESE 575 Fiber-Optic Communications
Introduction to optical communications via glass-fiber media. Pulse-code modulation and digital transmission methods, coding laws, receivers, bit-error rates. Types and properties of optical fibers; attenuation, dispersion, modes, numerical aperture. Light-emitting diodes and semiconductor laser sources; device structure, speed, brightness, modes, electrical properties, optical and spectral characteristics. Prerequisites: ESE 330, ESE 336. 
Credit 3 units. EN: TU

E35 ESE 581 Radar Systems
Credit 3 units. EN: TU

E35 ESE 582 Fundamentals and Applications of Modern Optical Imaging
Analysis, design and application of modern optical imaging systems with emphasis on biological imaging. First part of the course focuses on the physical principles underlying the operation of imaging systems and their mathematical models. Topics include ray optics (speed of light, refractive index, laws of reflection and refraction, plane surfaces, mirrors, lenses, aberrations), wave optics (amplitude and intensity, frequency and wavelength, superposition and interference, interferometry), Fourier optics (space-invariant linear systems, Huygens-Fresnel principle, angular spectrum, Fresnel diffraction, Fraunhofer diffraction, frequency analysis of imaging systems), and light-matter interaction (absorption, scattering, dispersion, fluorescence). Second part of the course compares modern quantitative imaging technologies including, but not limited to, digital holography, computational imaging, and super-resolution microscopy. Students evaluate and critique recent optical imaging literature. Prerequisites: ESE 318 and ESE 319 or their equivalents; ESE 330 or Physics 421 or equivalent. 
Credit 3 units. EN: TU

E35 ESE 584 Statistical Signal Processing for Sensor Arrays
Methods for signal processing and statistical inference for data acquired by an array of sensors, such as those found in radar, sonar and wireless communications systems. Multivariate statistical theory with emphasis on the complex multivariate normal distribution. Signal estimation and detection in noise with unknown statistics, signal estimation and detection in noise with unknown statistics, direction finding, spatial spectrum estimation, beam forming, parametric maximum-likelihood techniques. Subspace techniques, including MUSIC and ESPRIT. Performance analysis of various algorithms. Advanced topics may include structured covariance estimation, wide-band array processing, array calibration, array processing with polarization diversity, and space-time adaptive processing (STAP). Prerequisites: ESE 520, ESE 524, linear algebra, computer programming. 
Credit 3 units. EN: TU

E35 ESE 588 Quantitative Image Processing
Introduction to modeling, processing, manipulation and display of images. Application of two-dimensional linear systems to image processing. Two-dimensional sampling and transform methods.

EN: TU

E35 ESE 589 Biological Imaging Technology
This class develops a fundamental understanding of the physics and mathematical methods that underlie biological imaging and critically examine case studies of seminal biological imaging technology literature. The physics section examines how electromagnetic and acoustic waves interact with tissues and cells, how waves can be used to image the biological structure and function, image formation methods, and diffraction limited imaging. The math section examines image decomposition using basis functions (e.g., Fourier transforms), synthesis of measurement data, image analysis for feature extraction, reduction of multidimensional imaging datasets, multivariate regression, and statistical image analysis. Original literature on electron, confocal and two photon microscopy, ultrasound, computed tomography, functional and structural magnetic resonance imaging and other emerging imaging technology are critiqued. Credit 3 units.

EN: TU

E35 ESE 590 Electrical & Systems Engineering Graduate Seminar
This pass/fail course is required for the MS, DSc and PhD degrees in Electrical & Systems Engineering. A passing grade is required for each semester of enrollment and is received by attendance at regularly scheduled ESE seminars. MS students must attend at least three seminars per semester. DSc and PhD students must attend at least five seminars per semester. Part-time students are exempt except during their year of residency. Any student under continuing status is also exempt. Seminars missed in a given semester may be made up during the subsequent semester.

E35 ESE 596 Seminar in Imaging Science and Engineering
This seminar course consists of a series of tutorial lectures on Imaging Science and Engineering with emphasis on applications of imaging technology. Students are exposed to a variety of imaging applications that vary depending on the semester, but may include multispectral remote sensing, astronomical imaging, microscopic imaging, ultrasound imaging and tomographic imaging. Guest lecturers come from several parts of the university. This course is required of all students in the Imaging Science and Engineering program; the only requirement is attendance. This course is graded pass/fail. Prerequisite: admission to Imaging Science and Engineering program. Same as CSE 596 (when offered) and BME 506. Credit 1 unit.

E35 ESE 599 Master's Research
Prerequisite: Students must have the ESE Research/Independent Study Registration Form (PDF) (https://ese.wustl.edu/research/areas/Documents/Independent%20Study%20Form_1.pdf) approved by the department. Credit variable, maximum 3 units.

E35 ESE 600 Doctoral Research
Credit variable, maximum 9 units.