Electrical & Systems Engineering

About Electrical & Systems Engineering

The mission of our undergraduate programs is to instill in students the knowledge and perspective, appropriate both for a professional career and for the pursuit of advanced degrees, in fields that rely on key electrical engineering and systems principles and practices. Such principles and practices include rigorous quantitative reasoning and robust engineering design. This mission is accomplished by ensuring that students achieve both depth and breadth of knowledge in their studies and by maintaining a high degree of flexibility in the curriculum. Our programs also seek to provide good preparation for life, including the ability to communicate in written and oral forms and a desire to continue learning throughout life. In addition, they aim to provide the opportunity and training for students to acquire the skills and attitudes to become leaders.

The department offers courses of study leading to degrees in both electrical engineering and systems science and engineering. Opportunities for study and research currently available in the department include semiconductor theory and devices, optoelectronics, nanophotonics, communication theory and systems, information theory, signal and image processing, tomographic imaging, linear and nonlinear dynamics and control, robotics, identification and estimation, multisensor fusion and navigation, computational mathematics, optimization, optimal control, autonomous systems, operations research, and financial engineering. Students are encouraged to participate in research activities as soon as they have received training in the fundamentals appropriate for a given research area.

Electrical engineering is the profession for those intrigued with electrical phenomena and eager to contribute their skills to a society increasingly dependent on electricity and sophisticated electronic devices. It is a profession of broad scope with many specialty careers designed for engineers who seek an endless diversity of career paths on the cutting edge of technology. The Institute of Electrical and Electronics Engineers publishes transactions on about 60 different topics, from aerospace and electronic systems to visualization and computer graphics. This is a breadth so great that no single electrical engineering department can hope to span it. Moreover, those fields themselves encompass still more fascinating specialties. We give the basics; the future is yours to shape.

Systems science and engineering is based on an approach that views an entire system of components as an entity rather than simply as an assembly of individual parts; each component is designed to fit properly with the other components rather than to function by itself. The engineering and mathematics of systems is a rapidly developing field. It is one of the most modern segments of applied mathematics, as well as an engineering discipline. It is concerned with the identification, modeling, analysis, design and control of systems that are potentially as large and complex as the U.S. economy or as precise and vital as a space voyage. Its interests run from fundamental theoretical questions to the implementation of operational systems. It draws on the most modern and advanced areas of mathematics. A very important characteristic of the systems field is that its practitioners must, of necessity, interact within a wide interdisciplinary environment, not only with various engineers and scientists but also with economists, biologists or sociologists. Such interaction is both emphasized and practiced in the programs.

Our Department of Electrical & Systems Engineering offers a challenging basic curriculum, a broadly qualified faculty, and modern facilities so that students can receive a contemporary preparation for a career in electrical or systems engineering.

Undergraduate Degree Programs

The Department of Electrical & Systems Engineering (ESE) offers four undergraduate degree programs: two professional degrees and two applied science degrees. The two professional degrees are the Bachelor of Science in Electrical Engineering (BSEE) and the Bachelor of Science in Systems Science & Engineering (BSSSE). These two programs are accredited by the Engineering Accreditation Commission of ABET (http://www.abet.org). The two applied science degrees are the Bachelor of Science in Applied Science (Electrical Engineering) and the Bachelor of Science in Applied Science (Systems Science & Engineering). All programs have flexible curricula as well as specific requirements, and students may elect programs of study tailored to individual interests and professional goals.

In the professional BSEE curriculum, there are required courses in electrical circuits, signals and systems, digital systems and electromagnetic fields, along with laboratory and design courses, which provide students with a common core of experience. Subsequently, one may orient the program toward breadth, so that many disciplines within the profession are spanned or toward a specialty with more emphasis on depth in one or more disciplines. Areas of specialization include modern electronics, applied physics, telecommunications, control systems, and signal and image processing.

Students in the professional BSSSE degree program take required courses in engineering mathematics, signals and systems, operations research, and automatic control systems, along with laboratory and design courses. This program emphasizes the importance of real-world applications of systems theory, and accordingly students are required to take a concentration of courses in one of the traditional areas of engineering or science. There are numerous elective courses in control theory and systems, signal processing, optimization,
Students enrolled in any of the ESE undergraduate degree programs have a variety of opportunities to augment their educational experience at Washington University. Students may participate in the Pre-Medical Engineering program or in the Cooperative Education program. Some students pursue double majors, in which two sets of degree requirements, either within or outside the ESE department, are satisfied concurrently. The Process Control Systems program is one such double-degree program, involving the degrees Bachelor of Science in Systems Science & Engineering (BSSSE) and Bachelor of Science in Chemical Engineering (BSChem). Finally, students may earn both an undergraduate and a graduate degree through the school's five-year BS–Master's program.

Students who seek a broad undergraduate education in electrical engineering or systems science and engineering but plan on careers outside of engineering may pursue the applied science degrees: Bachelor of Science in Applied Science (Electrical Engineering) and Bachelor of Science in Applied Science (Systems Science & Engineering). These programs of study are appropriate for students planning to enter medical, law or business school, who desire a more technical undergraduate experience than what otherwise may be available to them.

The ESE department also offers a variety of educational opportunities for students enrolled in other departments. These include the second major in systems science and the second major in electrical engineering science, which are open to students inside as well as outside of the School of Engineering & Applied Science, such as the College of Arts & Sciences and the School of Business. They also include the minor in applied physics & electrical engineering, the minor in electrical engineering, the minor in energy engineering, the minor in mechatronics, the minor in robotics, and the minor in systems science & engineering.

**BS–Master’s Programs in Electrical & Systems Engineering**

Students enrolled in any of the undergraduate degree programs in the School of Engineering & Applied Science may choose to extend their educational experience by enrolling in a five-year BS–Master’s program. The Master of Science in Electrical Engineering (MSEE), Master of Science in Systems Science and Mathematics (MSSSM), Master of Control Engineering (MCE), Master of Engineering in Robotics (MER), and Master of Science in Engineering Data Analytics and Statistics (MSDAS) degrees are participating graduate degrees, and these may be combined with any undergraduate degree that provides the appropriate background.

General requirements for the BS–Master’s programs include the residency and other applicable requirements of the university and the School of Engineering & Applied Science, which are found elsewhere in this catalog. In summary, students must complete all the degree requirements for both the undergraduate and graduate degrees (at least 120 units plus 30 units; 150 units) but are not required to complete all the undergraduate degree requirements first.

**Phone:** 314-935-5565  
**Website:** [http://ese.wustl.edu](http://ese.wustl.edu)

**Faculty**

**Chair**  
R. Martin Arthur  
Newton R. and Sarah Louisa Glasgow Wilson Professor of Engineering  
PhD, University of Pennsylvania  
Ultrasonic 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 (https://engineering.wustl.edu/Profiles/Pages/Hiro-Mukai.aspx)
Professor
PhD, University of California, Berkeley
Theory and computational methods for optimization, optimal control, systems theory, electric power system operations, differential games

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

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

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

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, nanoelectronics, optoelectronics

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

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

**Senior Professors**

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, electrobiology, 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
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

Majors

Please refer to the sections below for information about the BS in Electrical Engineering (p. 4), BS in Systems Science & Engineering (p. 6), BS in Applied Science (Electrical Engineering) (p. 7), BS in Applied Science (Systems Science & Engineering) (p. 8), the Second Major in Electrical Engineering Science, Second Major in Systems Science and the Second Major in Financial Engineering (p. 9).

Bachelor of Science in Electrical Engineering

This professional degree program is accredited by the Engineering Accreditation Commission of ABET (http://www.abet.org).

Educational Objectives of the BSEE Degree Program

A. Our graduates will be engaged as practicing professionals in a broad range of careers in industry or government or be pursuing advanced degrees in academic graduate education in engineering or a related field.

B. Our graduates will function effectively as members of teams demonstrating sensitivity to professional and societal contexts, integrity and versatility.

Student Outcomes

Graduates of the BSEE program are expected to know or have:

(a) An ability to apply knowledge of mathematics, science and engineering

(b) An ability to design and conduct experiments, as well as to analyze and interpret data
(c) An ability to design a system, component or process to meet desired needs

(d) An ability to function on multidisciplinary teams

(e) An ability to identify, formulate and solve engineering problems

(f) An understanding of professional and ethical responsibility

(g) An ability to communicate effectively

(h) The broad education necessary to understand the impact of engineering solutions in a global and societal context

(i) A recognition of the need for, and an ability to engage in, lifelong learning

(j) A knowledge of contemporary issues

(k) An ability to use the techniques, skills, and modern engineering tools necessary for engineering practice

**BSEE Degree Requirements**

To obtain the degree Bachelor of Science in Electrical Engineering, students must complete a minimum of 120 units consistent with the residency and other applicable requirements of Washington University and the School of Engineering, and subject to the following program requirements.

1. Common Studies program of the School of Engineering: This includes courses in engineering, mathematics, chemistry, humanities, social sciences and technical writing. The required chemistry sequence is Chem 111A–Chem 151, although Chem 111A–Chem 112A–Chem 151–Chem 152 is recommended.

2. Engr 4501 Engineering Ethics and Sustainability (1 unit).

3. Two of the following three computer science courses: CSE 131 Computer Science I (3 units); CSE 132 Computer Science II (3 units); or CSE 247 Data Structures and Algorithms (3 units).

4. Engineering and science breadth requirements: 9 units in engineering or science outside of electrical engineering. These units must be taken in the following areas: biomedical engineering; chemical engineering; computer science and engineering; mechanical engineering; systems science and engineering; economics; mathematics; physics; biology; chemistry; earth and planetary sciences; and pre-medicine. These units must be at the 200 level or higher and shall not be used to satisfy the Common Studies requirements (item 1 above) or the CS requirement (item 3). Courses in other fields can be arranged with special departmental approval. Examples of engineering and science courses are MEMS 255 Engineering Mechanics II, EECE 210 Introduction to Environmental Engineering, EECE 203 Thermodynamics I in EECE, EECE 201 Engineering Analysis of Chemical Systems, CSE 247 Data Structures and Algorithms, Engr 324 From Concept to Market: The Business of Engineering, BME 240 Biomechanics, Physics 217 Introduction to Quantum Physics, Physics 318 Introduction to Quantum Physics II, MEMS 253 Engineering Mechanics I, Biol 2960 Principles of Biology I, Biol 2970 Principles of Biology II, Chem 261 Organic Chemistry I with Lab, Chem 262 Organic Chemistry II with Lab.

5. 28 units of required ESE courses:

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESE 230</td>
<td>Introduction to Electrical and Electronic Circuits</td>
<td>4</td>
</tr>
<tr>
<td>ESE 232</td>
<td>Introduction to Electronic Circuits</td>
<td>3</td>
</tr>
<tr>
<td>ESE 260</td>
<td>Introduction to Digital Logic and Computer Design</td>
<td>3</td>
</tr>
<tr>
<td>ESE 318</td>
<td>Engineering Mathematics A</td>
<td>3</td>
</tr>
<tr>
<td>ESE 319</td>
<td>Engineering Mathematics B</td>
<td>3</td>
</tr>
<tr>
<td>ESE 326</td>
<td>Probability and Statistics for Engineering</td>
<td>3</td>
</tr>
<tr>
<td>ESE 330</td>
<td>Engineering Electromagnetics Principles</td>
<td>3</td>
</tr>
<tr>
<td>ESE 351</td>
<td>Signals and Systems</td>
<td>3</td>
</tr>
<tr>
<td>ESE 498</td>
<td>Electrical Engineering Capstone</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Design Projects</td>
<td></td>
</tr>
</tbody>
</table>

Total Units: 28

6. Two upper-level laboratory courses (6 units) from the following list: ESE 331, ESE 435, ESE 447, ESE 448, ESE 465, ESE 488. The selection must contain at least one course from ESE 331, ESE 435, ESE 465, ESE 488.

7. 15 units of elective ESE courses in electrical engineering subjects, from the following list: ESE 330–399, ESE 400, ESE 405, ESE 407, ESE 415, ESE 425, ESE 429–499, ESE 503–589.

8. The entire course sequence for the BSEE containing engineering topics of at least 45 units. The numbers of engineering topic units assigned to undergraduate courses in the School of Engineering & Applied Science vary from none (0) to the number of credits given to the course. For the precise number for each course, please refer to the table of Topics Units — Engineering Courses provided by Engineering Student Services (http://engineering.wustl.edu/current-students/student-services/Pages/default.aspx).

9. Limitations. No more than 3 credits of 500-level courses may be applied toward the EE elective requirement (item 7).

10. Limitations. No more than 6 units of the combined units of ESE 400 Independent Study and ESE 497 Undergraduate Research (including ESE 497A and ESE 497B) may be applied toward the EE elective requirement (Item 7) of the BSEE degree. The balance of combined units, if there are any left, are allowed as free electives to satisfy the requirement on the total number of units.

11. The courses taken to satisfy the following BSEE degree requirements must be taken for a letter grade and not on a pass/fail basis: Item 5 (required ESE courses), Item 6...
(upper-level laboratory courses) and Item 7 (elective ESE courses).

Most students acquire more than 120 credit units. For a typical sequence of subjects for the Bachelor of Science in Electrical Engineering degree, please refer to the following tables:

- Sample Electrical Engineering Curriculum (http://bulletin.wustl.edu/undergrad/engineering/electrical/samplecurriculum)
- Sample Pre-Med Electrical Engineering Curriculum (http://bulletin.wustl.edu/undergrad/engineering/electrical/premedcurriculum)

For more information on BS in Electrical Engineering curriculums, please visit the ESE website (http://ese.wustl.edu).

**Bachelor of Science in Systems Science & Engineering**

This professional degree program is accredited by the Engineering Accreditation Commission of ABET (http://www.abet.org).

**Objectives and Requirements**

Key points:

- Systems Engineering: how to integrate different components in engineering systems
- Operations Research: mathematical solutions to business problems
- Pre-Financial Engineering: the best preparation for the MS in Financial Engineering
- Applied Mathematics
- Control Engineering: how to control jet airplanes, electric power grids, and the nation’s economy
- Ideal for students strong in math and physics
- Ideal for students interested in engineering and business
- Ideal for students interested in a second degree
- The most mathematical program in the School of Engineering & Applied Science
- The most flexible professional program in the School of Engineering & Applied Science

This program educates students in the engineering and science of systems. Graduates are expected to have mathematical competence and knowledge of systems analysis, control, design methods, numerical methods, differential equations, dynamic systems theory, automatic control theory, system stability, estimation, optimization, modeling, identification, simulation and basic computer programming. Graduates will have an engineering outlook and engineer’s competence of their own and be able to interact fully with other engineers. They also will possess sufficient proficiency in computer use to design algorithms for simulation, estimation, control and optimization.

The engineering departments of high-technology industries are staffed by large numbers of engineers with this type of expertise. However, graduates are by no means restricted to careers in traditional industry or in high-technology industries. Within the outlined framework, a salient feature of the program is its flexibility and interdisciplinary nature. It is possible for students to orient study toward preparation for systems science and engineering work in large complex systems such as transportation or power or communications networks or in societal systems such as the economy, ecology, the cities or biological systems. Students may wish to prepare for work along theoretical or professional lines. There is ample room in the program structure to accommodate all these interests and to make preparation at the BS level ideally suited for a student’s future plans and interests.

**Educational Objectives of the BSSSE Degree Program**

A. Our graduates will be engaged as practicing professionals in a broad range of careers in industry or government or be pursuing advanced degrees in academic graduate education in engineering or a related field.

B. Our graduates will function effectively as members of teams demonstrating sensitivity to professional and societal contexts, integrity and versatility.

**Student Outcomes**

Graduates of the BSSSE program are expected to know or have:

(a) An ability to apply knowledge of mathematics, science and engineering

(b) An ability to design and conduct experiments, as well as to analyze and interpret data

(c) An ability to design a system, component, or process to meet desired needs

(d) An ability to function on multidisciplinary teams

(e) An ability to identify, formulate and solve engineering problems

(f) An understanding of professional and ethical responsibility

(g) An ability to communicate effectively

(h) The broad education necessary to understand the impact of engineering solutions in a global and societal context

(i) A recognition of the need for, and an ability to engage in, lifelong learning

(j) A knowledge of contemporary issues

(k) An ability to use the techniques, skills, and modern engineering tools necessary for engineering practice
BSSSE Degree Requirements

The course sequence designed to achieve the type of education outlined above requires at least 120 units, satisfies the residency and other applicable requirements of Washington University and the School of Engineering & Applied Science, and meets the following program requirements:

1. Common Studies program of the School of Engineering & Applied Science. This includes courses in engineering, mathematics, physics, chemistry, humanities, social sciences and technical writing. The required chemistry sequence is Chem 111A-Chem 151.

2. Engr 4501 Engineering Ethics and Sustainability (1 unit).

3. Required courses in systems science and engineering: ESE 205 Introduction to Engineering Design (3 units); Math 309 Matrix Algebra (3 units); ESE 318 Engineering Mathematics A (3 units) and ESE 319 Engineering Mathematics B (3 units); ESE 326 Probability and Statistics for Engineering (3 units); ESE 351 Signals and Systems (3 units); ESE 403 Operations Research (3 units); ESE 441 Control Systems (3 units); ESE 448 Systems Engineering Laboratory (3 units); and ESE 499 Systems Science and Engineering Capstone Design Project (3 units).

4. Two of the following three computer science courses: CSE 131 Computer Science I (3 units); CSE 247 Data Structures and Algorithms (3 units); and CSE 132 Computer Science II (3 units). Students are encouraged to take CSE 131 Computer Science I and CSE 247 Data Structures and Algorithms. The other possible sequence is CSE 131 and CSE 132.

5. One of the following three laboratory courses: ESE 447 Robotics Laboratory (3 units), ESE 449 Digital Process Control Laboratory (3 units), ESE 488 Signals and Communication Laboratory (3 units). ESE 449 is only recommended to students with a chemical engineering background.

6. 12 units in elective courses in systems science and engineering: ESE 400 through 428; ESE 437; ESE 440 through 459; ESE 470 through 489; ESE 497; ESE 500 through 529; ESE 540 through 559. Up to 3 units of the following business courses may be part of the 12 units of SSE electives: OSCM 356 Operations Management, OSCM 458 Operations Planning and Control, OMM 576 Foundations of Supply Chain Management, OMM 577 Information Technology and Supply Chain Management.

7. 12 units in engineering concentration outside of systems science and engineering. These units must all be taken in one of the following engineering areas: Biomedical Engineering, Chemical Engineering, Computer Science & Engineering, Electrical Engineering (ESE 102; ESE 230 through 239; ESE 260 through 290; ESE 330 through 339; ESE 360 through 390; ESE 429 through 439; ESE 460 through 469; 490 through 496; ESE 498; ESE 530 through 539; ESE 560 through 589), or Mechanical Engineering & Materials Science. Of the 12 units, 9 units must be at the 200 level or higher. Sequences for concentrations in economics, mathematics, physics, pre-medicine and other fields can be arranged with special departmental approval to meet a student's specific needs. When a non-engineering discipline is chosen as the outside concentration, the student needs to pay special attention to the next requirement, which is required of all students, and make sure that enough engineering contents are obtained from the other courses. The use of basic required courses to fulfill the requirement for an outside concentration is not permitted.

8. The entire course sequence for the BSSSE, containing engineering topics of at least 45 units. The numbers of engineering topic units assigned to undergraduate courses in the School of Engineering & Applied Science vary from none (0) to the number of credits given to the course. For the precise number for each course, please refer to the table of Topics Units — Engineering Courses provided by Engineering Student Services (http://engineering.wustl.edu/current-students/student-services/Pages/default.aspx).

9. Limitations. No more than 6 units of the combined units of ESE 400 Independent Study and ESE 497 Undergraduate Research (including 497A and 497B) may be applied toward the SSE elective requirement (item 6) of the BSSSE degree. Any remaining combined units are allowed as free electives to satisfy the requirement on the total number of units.

10. The courses taken to satisfy the following BSSSE degree requirements must be taken for a letter grade and not on a pass/fail basis: item 3 (required ESE courses), item 5 (elective laboratory course) and item 6 (elective ESE courses).

The program requirements for the BS in Systems Science & Engineering allow a double major with another department. Changes in the program to accommodate such double majors may be made with departmental approval. For a sample program for the BS in Systems Science & Engineering, please refer to the following tables:


For more information on BS in Systems Science & Engineering curriculums, please visit the ESE website (http://ese.wustl.edu).

Bachelor of Science in Applied Science (Electrical Engineering)

Students who do not plan to pursue a career in electrical engineering but seek a strong foundation in the principles of electrical engineering may choose the Bachelor of Science
in Applied Science (Electrical Engineering). The program ensures that the student learns the foundations of electrical engineering through breadth requirements. In addition, there is flexibility in selecting upper-level courses to meet the student's individual objectives. This program also may be attractive for students interested in obtaining multiple degrees because the requirements are less strict than for the BSEE degree. Historically students have matched a degree in electrical engineering with degrees in other engineering disciplines, in the natural sciences, in music, in history and in business; other combinations are possible. This also may be an attractive option for students planning graduate studies in a variety of disciplines including medicine, law or business. This applied science degree is not accredited by the Engineering Accreditation Commission of ABET (http://www.abet.org).

The degree requirements include the residency and general requirements of the university and the School of Engineering & Applied Science and:

<table>
<thead>
<tr>
<th>Courses</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Humanities and social sciences electives</td>
<td>18</td>
</tr>
<tr>
<td>Mathematics, science and engineering electives</td>
<td>24</td>
</tr>
<tr>
<td>Required courses in electrical engineering (ESE 230, ESE 232, ESE 330 and ESE 351)</td>
<td>13</td>
</tr>
<tr>
<td>Computer Science requirement (CSE 131)</td>
<td>3</td>
</tr>
<tr>
<td>Upper-level elective courses in electrical engineering (ESE 260, ESE 326, ESE 330–399, ESE 400, ESE 405, ESE 407, ESE 415, ESE 425, ESE 429–499, ESE 503–589)</td>
<td>21</td>
</tr>
<tr>
<td>Free electives</td>
<td>41</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>120</strong></td>
</tr>
</tbody>
</table>

The program must include at least 48 units at the 300 level or higher.

**Bachelor of Science in Applied Science (Systems Science & Engineering)**

This program provides a student with the opportunity to prepare their academic career with maximum flexibility, but with enough organization to assure substantive, consistent training in systems science methodology and outlook. This program is recommended if students wish to pursue a program that does not follow conventional lines. It is an especially advantageous degree for a double major in association with mathematics, physics, economics or another engineering discipline. The program can be planned to provide a desirable background for graduate work in biological, medical or management fields. This applied science degree is not accredited by the Engineering Accreditation Commission of ABET (http://www.abet.org).

The degree requirements include the residency and general requirements of the university and the School of Engineering and:

<table>
<thead>
<tr>
<th>Courses</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Humanities and social sciences electives</td>
<td>18</td>
</tr>
<tr>
<td>Mathematics, science and engineering electives</td>
<td>24</td>
</tr>
<tr>
<td>Required courses: ESE 205, ESE 351, ESE 403, and ESE 441</td>
<td>12</td>
</tr>
<tr>
<td>Computer Science requirement (CSE 131)</td>
<td>3</td>
</tr>
<tr>
<td>Systems science and engineering electives</td>
<td>15</td>
</tr>
<tr>
<td>Free electives</td>
<td>48</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>120</strong></td>
</tr>
</tbody>
</table>

The program must include at least 48 units at the 300 level or higher.

**The Second Major in Electrical Engineering Science**

A second major in electrical engineering science is ideal for students majoring in many areas, such as mathematics, physics, chemistry and biology. Students in the School of Engineering & Applied Science as well as the other undergraduate divisions at Washington University now have the opportunity to pursue a second major in electrical engineering science. Students are not allowed to add this second major to either the BS in Electrical Engineering or the BS in Applied Science (Electrical Engineering).

The requirements for a second major in electrical engineering science are:

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESE 230</td>
<td>Introduction to Electrical and Electronic Circuits</td>
<td>4</td>
</tr>
<tr>
<td>ESE 260</td>
<td>Introduction to Digital Logic and Computer Design</td>
<td>3</td>
</tr>
<tr>
<td>ESE 351</td>
<td>Signals and Systems</td>
<td>3</td>
</tr>
</tbody>
</table>

And one of the following:

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESE 232</td>
<td>Introduction to Electronic Circuits</td>
<td>3</td>
</tr>
<tr>
<td>ESE 318</td>
<td>Engineering Mathematics A</td>
<td>3</td>
</tr>
<tr>
<td>ESE 319</td>
<td>Engineering Mathematics B</td>
<td>3</td>
</tr>
<tr>
<td>ESE 326</td>
<td>Probability and Statistics for Engineering</td>
<td>3</td>
</tr>
<tr>
<td>ESE 330</td>
<td>Engineering Electromagnetics Principles</td>
<td>3</td>
</tr>
</tbody>
</table>

And seven 3-unit ESE courses in the Electrical Engineering area chosen from:
The above program assumes the completion of the following courses:

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Math 132 &amp; Math 233</td>
<td>Calculus II and Calculus III</td>
<td>6</td>
</tr>
<tr>
<td>Math 217</td>
<td>Differential Equations</td>
<td>3</td>
</tr>
<tr>
<td>CSE 131</td>
<td>Computer Science I</td>
<td>3</td>
</tr>
<tr>
<td>Physics 117A</td>
<td>General Physics I</td>
<td>4</td>
</tr>
<tr>
<td>Physics 118A</td>
<td>General Physics II</td>
<td>4</td>
</tr>
</tbody>
</table>

Students may petition to substitute electrical science-oriented courses from other disciplines in Arts & Sciences for up to two of the above 11 courses (for example, certain courses in physics or applied mathematics). When such substitutions are employed, the total number of units for non-Arts & Sciences courses is 31 or 32 units. Within this second major in electrical engineering science, areas of concentration are possible in: applied physics, signal processing, and control systems. The second major in the electrical engineering science program comprises a total of 34 or 35 units. To design a customized program, contact the director of the program Professor R. Martin Arthur (rma@wustl.edu).

The Second Major in Systems Science

A second major in systems science is ideal for study in many areas such as physics, chemistry, economics, finance, supply chain management, and computational biology. Students in the School of Engineering as well as the other undergraduate divisions at Washington University have the opportunity to pursue a second major in systems science in the Preston M. Green Department of Electrical & Systems Engineering in the School of Engineering & Applied Science. Students are not allowed to add this second major to either the BS in SSE or the BS in Applied Science (SSE).

The requirements for a second major in systems science are:

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESE 205</td>
<td>Introduction to Engineering Design</td>
<td>3</td>
</tr>
<tr>
<td>Math 309</td>
<td>Matrix Algebra</td>
<td>3</td>
</tr>
<tr>
<td>ESE 351</td>
<td>Signals and Systems</td>
<td>3</td>
</tr>
</tbody>
</table>

One of the following:

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESE 318</td>
<td>Engineering Mathematics A</td>
<td>3</td>
</tr>
<tr>
<td>ESE 319</td>
<td>Engineering Mathematics B</td>
<td>3</td>
</tr>
<tr>
<td>ESE 326</td>
<td>Probability and Statistics for Engineering</td>
<td>3</td>
</tr>
<tr>
<td>ESE 441</td>
<td>Control Systems</td>
<td>3</td>
</tr>
</tbody>
</table>

Eight 3-unit ESE courses in the Systems area chosen from:

- ESE 318 through 326
- ESE 400 through 428
- ESE 437
- ESE 440 through 459
- ESE 470 through 489
- ESE 500 through 529
- ESE 540 through 559

Students may petition to substitute systems-oriented courses from other disciplines in Arts & Sciences for two of these eight courses (for example, courses in computational physics, econometrics or computational mathematics). When such substitutions are employed, the total number of units for non-Arts & Sciences courses will be 30 units.

Within this second major in systems science, areas of concentration are possible in: robotics, control systems, and operations research.

This totals 34 to 40 units of systems science, depending on student's use of the substitution option for upper-level electives. To design a customized program, contact the departmental associate chair Professor Hiro Mukai (https://ese.wustl.edu/faculty/Pages/default.aspx?bio=75) or the director of the program Professor Heinz Schaettler (https://engineering.wustl.edu/Profiles/Pages/Heinz-Schaettler.aspx).

The Second Major in Financial Engineering

A second major in financial engineering is ideal for students who are interested in careers or graduate school in financial engineering, quantitative finance, or related fields. This program covers classes in engineering, computer science and business.

Background Course Work: 18 units

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSE 131</td>
<td>Computer Science I</td>
<td>3</td>
</tr>
<tr>
<td>ESE 326</td>
<td>Probability and Statistics for Engineering</td>
<td>3</td>
</tr>
<tr>
<td>or QBA 121</td>
<td>Managerial Statistics II</td>
<td>3</td>
</tr>
<tr>
<td>or Econ 413</td>
<td>Introduction to Econometrics</td>
<td>3</td>
</tr>
</tbody>
</table>
or Math 439  |  Linear Statistical Models  |  
Math 217  |  Differential Equations  |  3  
Math 233  |  Calculus III  |  3  
Math 309  |  Matrix Algebra  |  3  
MEC 290  |  Microeconomics  |  3  
or Econ 4011  |  Intermediate Microeconomic Theory  |  

Engineering Professional Core Requirements: 15 units

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSE 240</td>
<td>Logic and Discrete Mathematics</td>
<td>3</td>
</tr>
<tr>
<td>CSE 247</td>
<td>Data Structures and Algorithms</td>
<td>3</td>
</tr>
<tr>
<td>CSE 417T</td>
<td>Introduction to Machine Learning</td>
<td>3</td>
</tr>
</tbody>
</table>
or CSE 427S | Cloud Computing with Big Data Applications | 
| ESE 403  | Operations Research                        | 3     |
or ESE 415 | Optimization                               |       |
| ESE 427  | Financial Mathematics                      | 3     |

Olin Professional Core Requirements: 9 units

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACCT 2610</td>
<td>Principles of Financial Accounting</td>
<td>3</td>
</tr>
<tr>
<td>FIN 340</td>
<td>Capital Markets and Financial Management</td>
<td>3</td>
</tr>
<tr>
<td>FIN 441</td>
<td>Investments</td>
<td>3</td>
</tr>
</tbody>
</table>

Olin Elective Courses: 6 units minimum

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>FIN 500Q</td>
<td>Quantitative Risk Management</td>
<td>3</td>
</tr>
<tr>
<td>FIN 537</td>
<td>Advanced Derivative Securities</td>
<td>3</td>
</tr>
<tr>
<td>FIN 539</td>
<td>Mathematical Finance</td>
<td>1.5</td>
</tr>
<tr>
<td>FIN 551</td>
<td>Advanced Fixed Income and Credit Risk Modeling</td>
<td>2</td>
</tr>
<tr>
<td>FIN 552</td>
<td>Fixed Income Derivatives</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Minors

Please refer to the sections below for information about the minors in applied physics & electrical engineering (p. 10), electrical engineering (p. 11), energy engineering (ESE) (p. 11), mechatronics (ESE) (p. 11), robotics (p. 12), and systems science & engineering (p. 12).

The Minor in Applied Physics & Electrical Engineering

(Program Director: Dr. Jung-Tsung Shen (https://engineering.wustl.edu/Profiles/Pages/Jung-Tsung-Shen.aspx))

Units required: 19

The minor in applied physics & electrical engineering provides students with course work that will enhance their background, knowledge and skills in the topical area of applied physics and electrical engineering. This program covers classes in several fields of science and engineering, encompassing electronics, solid-state devices, applied electromagnetics, RF and microwave technology, fiber-optic communication, applied optics, nanophotonics, sensors, and medical and biological imaging technology.

This program consists of six courses total: one required course, two core courses and three electives. At least three courses among the six courses must be ESE courses taught by the ESE department and not taught by other departments by means of cross-listing. Students who complete the following requirements in Applied Physics & Electrical Engineering subjects at Washington University as specified below may be awarded a minor in applied physics & engineering.

Target students: Students who are interested in applied physics and electrical engineering applications.

Prerequisite: ESE 318 Engineering Mathematics A, or equivalent, is recommended.

Course requirements:

1. **Required course:**
   ESE 230 Introduction to Electrical and Electronic Circuits
2. **One core lab course** from the following list:
   - ESE 331 Electronics Laboratory; or Physics 321 Electronics Laboratory
   - ESE 435 Electrical Energy Laboratory
3. **One core course** from the following list:
   - ESE 232 Introduction to Electronic Circuits
   - ESE 330 Engineering Electromagnetics Principles; or Physics 421 Electricity and Magnetism
   - ESE 337 Electronic Devices and Circuits
   - ESE 444 Sensors and Actuators
   - Physics 471 Quantum Mechanics
4. **Three electives** from the following list. These three courses (i) must exclude the course selected in the requirement (3) above, and (ii) must include at least one Physics course:

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESE 232</td>
<td>Introduction to Electronic Circuits</td>
<td>3</td>
</tr>
<tr>
<td>ESE 330</td>
<td>Engineering Electromagnetics Principles</td>
<td>3</td>
</tr>
<tr>
<td>ESE 332</td>
<td>Power, Energy and Polyphase Circuits</td>
<td>3</td>
</tr>
<tr>
<td>ESE 337</td>
<td>Electronic Devices and Circuits</td>
<td>3</td>
</tr>
<tr>
<td>ESE 433</td>
<td>Radio Frequency and Microwave Technology for Wireless Systems</td>
<td>3</td>
</tr>
<tr>
<td>ESE 434</td>
<td>Solid-State Power Circuits and Applications</td>
<td>3</td>
</tr>
<tr>
<td>ESE 438</td>
<td>Applied Optics</td>
<td>3</td>
</tr>
<tr>
<td>ESE 444</td>
<td>Sensors and Actuators</td>
<td>3</td>
</tr>
<tr>
<td>ESE 531</td>
<td>Nano and Micro Photonics</td>
<td>3</td>
</tr>
<tr>
<td>ESE 532</td>
<td>Introduction to Nano-Photonic Devices</td>
<td>3</td>
</tr>
<tr>
<td>ESE 534</td>
<td>Special Topics in Advanced Electrodynamics</td>
<td>3</td>
</tr>
<tr>
<td>ESE 575</td>
<td>Fiber-Optic Communications</td>
<td>3</td>
</tr>
<tr>
<td>Physics 463</td>
<td>Statistical Mechanics and Thermodynamics</td>
<td>3</td>
</tr>
<tr>
<td>Physics 471</td>
<td>Quantum Mechanics</td>
<td>3</td>
</tr>
<tr>
<td>Physics 472</td>
<td>Solid State Physics</td>
<td>3</td>
</tr>
<tr>
<td>Physics 537</td>
<td>Kinetics of Materials</td>
<td>3</td>
</tr>
</tbody>
</table>

The Minor in Electrical Engineering

Units required: 16

**Required courses:**

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESE 230</td>
<td>Introduction to Electrical and Electronic Circuits</td>
<td>4</td>
</tr>
<tr>
<td>ESE 330</td>
<td>Engineering Electromagnetics Principles</td>
<td>3</td>
</tr>
<tr>
<td>ESE 351</td>
<td>Signals and Systems</td>
<td>3</td>
</tr>
</tbody>
</table>

**Electives:** Students must select two electrical engineering elective courses from the following list:

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESE 232</td>
<td>Introduction to Electronic Circuits</td>
<td>3</td>
</tr>
<tr>
<td>ESE 260</td>
<td>Introduction to Digital Logic and Computer Design</td>
<td>3</td>
</tr>
<tr>
<td>ESE 330−399</td>
<td>with the exception of ESE 431</td>
<td></td>
</tr>
</tbody>
</table>

For more information, contact the director for the minor (Professor R. Martin Arthur (rma@wustl.edu)) or visit the ESE website (http://ese.wustl.edu).

The Minor in Energy Engineering (ESE)

This minor will provide students with course work that will enhance their background, knowledge and skills in the topical area of energy engineering. The minor covers classes in several fields of science and engineering, encompassing the Department of Energy, Environmental & Chemical Engineering; the Department of Electrical & Systems Engineering; and the Department of Mechanical Engineering & Materials Science. A minor in energy engineering requires the completion of 18 units. It is open to undergraduate students pursuing an engineering major, students from the sciences (biology, chemistry, physics) in Arts & Sciences, and students pursuing the environmental studies major. The detailed requirements for the minor can be found on the Energy, Environmental & Chemical Engineering Minors page (http://bulletin.wustl.edu/undergrad/engineering/energy-environmental-chemical/#minors). Questions regarding the minor should be directed to a member of the committee for the energy engineering minor: Professor Pratim Biswas (EECE) (https://engineering.wustl.edu/Profiles/Pages/Pratim-Biswas.aspx), Professor Hiro Mukai (ESE) (https://engineering.wustl.edu/Profiles/Pages/Hiro-Mukai.aspx) or Professor David Peters (MEMS) (https://engineering.wustl.edu/Profiles/Pages/David-Peters.aspx).

Committee to Oversee Energy Engineering Minor

Pratim Biswas (EECE, Coordinator)

Hiro Mukai (ESE)

David Peters (MEMS)

The committee ensures that any course added to the above lists contains a significant amount of energy topics and that the entire program be cohesive.

Visit the ESE website (http://ese.wustl.edu) for more information.

The Minor in Mechatronics (ESE)

(Program Director: Heinz Schaettler)

Advancements in power electronics, electronic sensors, and computer hardware and software have led to an expanding role for “smart” systems, which combine electronic and mechanical components. Automotive examples illustrate this point. The replacement of carburetors by fuel injection systems is almost universal, and hybrid/electric cars are replacing traditional automobiles. Not only are auxiliary devices such as fuel pumps, air bags and air conditioner compressors driven by electric motors controlled by microprocessors, but fundamental
components such as intake and outtake valves soon will be driven in this way. The internal combustion engine itself may be replaced by fuel cells and motors. Medical devices, micro-electromechanical systems, robots, fly-by-wire aircraft and wind turbines also all rely on electronic sensing of mechanical parameters and actuation of motion. These examples suggest strongly that engineers who are adept in the design, analysis and simulation of electromechanical systems will be in demand. The minor in mechatronics is created to encourage our students to study this important subject and provide recognition to those who do so.

This program is primarily designed for students in the ESE and MEMS departments and has been approved by the two departments. It is available for others as well.

The proposed minor program consists of four required courses, two electives and one prerequisite:

**Four required courses:**

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEMS 255</td>
<td>Engineering Mechanics II (Dynamics)</td>
<td>3</td>
</tr>
<tr>
<td>MEMS 411</td>
<td>Mechanical Engineering Design Project (Mechatronics project)</td>
<td>3</td>
</tr>
<tr>
<td>ESE 444</td>
<td>Sensors and Actuators</td>
<td>3</td>
</tr>
<tr>
<td>ESE 446</td>
<td>Robotics: Dynamics and Control</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td><strong>Total Units</strong></td>
<td><strong>12</strong></td>
</tr>
</tbody>
</table>

**Two electives from the following:**

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEMS 4301</td>
<td>Modeling, Simulation and Control</td>
<td>3</td>
</tr>
<tr>
<td>or ESE 441</td>
<td>Control Systems</td>
<td></td>
</tr>
<tr>
<td>MEMS 4310</td>
<td>Dynamics and Vibrations</td>
<td>3</td>
</tr>
<tr>
<td>MEMS 5101</td>
<td>Analysis and Design of Fluid-Power Systems</td>
<td>3</td>
</tr>
<tr>
<td>ESE 337</td>
<td>Electronic Devices and Circuits</td>
<td>3</td>
</tr>
<tr>
<td>ESE 482</td>
<td>Digital Signal Processing</td>
<td>3</td>
</tr>
<tr>
<td>CSE 467S</td>
<td>Embedded Computing Systems</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td><strong>Total Units</strong></td>
<td><strong>12</strong></td>
</tr>
</tbody>
</table>

**Prerequisite:**

Basic programming course: CSE 131 Computer Science I

Visit the ESE website (http://ese.wustl.edu) for more information.

---

**The Minor in Robotics**

Robotic systems have wide applications in modern technology and manufacturing. Robots can vary in complexity and use, from microrobots for surgical procedures to moderate-size robots common in manufacturing and underwater exploration to macrorobots used for disposal of nuclear wastes and as arms on space-station modules. The program designed for a minor in robotics provides a fundamental understanding of robotic operation and preliminary training in design and use of robots.

**Units required: 18**

**Prerequisites:**

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Math 217</td>
<td>Differential Equations</td>
<td>3</td>
</tr>
<tr>
<td>Physics 117A</td>
<td>General Physics I</td>
<td>4</td>
</tr>
<tr>
<td>or Physics 197</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Physics 118A</td>
<td>General Physics II</td>
<td>4</td>
</tr>
<tr>
<td>or Physics 198</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CSE 131</td>
<td>Computer Science I</td>
<td>3</td>
</tr>
</tbody>
</table>

**Required courses:**

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEMS 255</td>
<td>Engineering Mechanics II</td>
<td>3</td>
</tr>
<tr>
<td>ESE 351</td>
<td>Signals and Systems</td>
<td>3</td>
</tr>
<tr>
<td>or MEMS 4310</td>
<td>Dynamics and Vibrations</td>
<td></td>
</tr>
<tr>
<td>ESE 446</td>
<td>Robotics: Dynamics and Control</td>
<td>3</td>
</tr>
<tr>
<td>ESE 447</td>
<td>Robotics Laboratory</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td><strong>Total Units</strong></td>
<td><strong>12</strong></td>
</tr>
</tbody>
</table>

Plus two courses chosen with the approval of the director of the program for a minor in robotics. Suggested courses are:

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSE 417T</td>
<td>Introduction to Machine Learning</td>
<td>3</td>
</tr>
<tr>
<td>CSE 452A</td>
<td>Computer Graphics</td>
<td>3</td>
</tr>
<tr>
<td>CSE 546T</td>
<td>Computational Geometry</td>
<td>3</td>
</tr>
<tr>
<td>ESE 407</td>
<td>Analysis and Simulation of Discrete Event Systems</td>
<td></td>
</tr>
<tr>
<td>ESE 435</td>
<td>Electrical Energy Laboratory</td>
<td>3</td>
</tr>
<tr>
<td>ESE 441</td>
<td>Control Systems</td>
<td>3</td>
</tr>
<tr>
<td>or MEMS 4301</td>
<td>Modeling, Simulation and Control</td>
<td></td>
</tr>
<tr>
<td>MEMS 3110</td>
<td>Machine Elements</td>
<td>3</td>
</tr>
</tbody>
</table>

To find out more about this minor, contact the director (Heinz Schaettler (https://engineering.wustl.edu/Profiles/Pages/Heinz-Schaettler.aspx)) of the program.
Materials and methods:

A hands-on introduction to electrical engineering to put the fun into the electrical engineering fundamentals. Experiments, using ammeters and voltmeters. Energy and maximum electrical power transfer. Computer simulations of circuits. Reactive circuits, inductors, capacitors, mutual inductance, electrical transformers, energy storage, and energy conservation. RL, RC and RLC circuit transient responses, biological cell including ultrasound imaging, computed tomography, DC motors, analog to digital converters and credit card readers. Students work in groups of two in the newly renovated Urbauer 115 laboratory. Each station is equipped with modern electronic test equipment and a computer with an integrated Data Acquisition system. Using this lab equipment, students design and build solutions to the exercises. The students also learn to program in LabVIEW to control the Data Acquisition system and process the acquired signals. Also, throughout the semester, presentations are given by the ESE faculty about their research. Credit 1 unit. EN: TU

E35 ESE 101 Introduction to Engineering Tools: MATLAB and Simulink
MATLAB and Simulink are important tools in quickly analyzing different designs in many engineering disciplines and are also perhaps the most used software in many engineering schools. Gain skills in the basics of the array-based language MATLAB to write programs, including scripts and functions, to calculate and display variables and images. Learn the basics of Simulink to build and simulate models from standard blocks. Discover both MATLAB and Simulink in an environment with supervised practice and hands-on experience. Practice problems are chosen from different engineering fields as well as from a few socio-economic fields so that students can see the software being exploited in real life applications. This is a pass/fail course. Prerequisite: freshman standing.
Credit 1 unit. EN: TU

E35 ESE 103 Introduction to Electrical Engineering
A hands-on introduction to electrical engineering to put the fun into the electrical engineering fundamentals. Experiments are designed to be easy to conduct and understand. Some of the technologies explored are used in a variety of applications
action potentials due to Na and K ions. AC circuits, complex impedance, RMS current and voltage. Electrical signal amplifiers and basic operational amplifier circuits. Inverting, noninverting, and difference amplifiers. Voltage gain, current gain, input impedance, and output impedance. Weekly laboratory exercises related to the lectures are an essential part of the course. Prerequisite: Physics 118A. Corequisite: Math 217.
Credit 4 units. EN: TU

E35 ESE 232 Introduction to Electronic Circuits
Analysis and design of linear electronic circuits. Terminal characteristics of active semiconductor devices. Incremental and DC models for diodes, metal-oxide-semiconductor field effect transistors (MOSFETs) and bipolar junction transistors (BJTs). Design and analysis of single- and multistage amplifiers. Volatile and nonvolatile memories. Understanding of common application circuits (e.g., operational amplifier, memories) in integrated circuit chips. Semester-long design project. Prerequisite: ESE 230.
Credit 3 units. EN: TU

E35 ESE 260 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 260M
Credit 3 units. EN: TU

E35 ESE 297 Introduction to ESE Undergraduate Research Projects
This course is offered to students at all levels from all departments. The course is designed to give students some hands-on experience by implementing projects that use the lab PCs, the sbRIO robots from National Instruments, acoustic sensors, bio-medical sensors and 3D cameras. These projects are implemented in LabVIEW and Matlab and should prepare the students to work on topics that include the Robotic Sensing Undergraduate Research Projects in subsequent semesters. Note that under ESE 497 Undergraduate Research, students may select the Robotic Sensing Projects as well as other projects. Working in groups, students implement algorithms that run on PCs and our wireless robotic platforms to track a moving audio source. Also, they use an EEG system to implement a Brain Computer Interface (BCI) project and work with the new Kinect camera from Microsoft. Corequisite: CSE 131 or equivalent.
Credit 3 units.

E35 ESE 318 Engineering Mathematics A
Laplace transforms; matrix algebra; vector spaces; eigenvalues and eigenvectors; vector differential calculus and vector integral calculus in three dimensions. Prerequisites: Math 233 and Math 217 or their equivalents.
Credit 3 units.

E35 ESE 319 Engineering Mathematics B
Power series and Frobenius series solutions of differential equations; Legendre's equation; Bessel's equation; Fourier series and Fourier transforms; Sturm-Liouville theory; solutions of partial differential equations; wave and heat equations. Prerequisites: Math 233 and Math 217 or their equivalents.
Credit 3 units.

E35 ESE 326 Probability and Statistics for Engineering
Study of probability and statistics together with engineering applications. Probability and statistics: random variables, distribution functions, density functions, expectations, means, variances, combinatorial probability, geometric probability, normal random variables, joint distribution, independence, correlation, conditional probability, Bayes theorem, the law of large numbers, the central limit theorem. Applications: reliability, quality control, acceptance sampling, linear regression, design and analysis of experiments, estimation, hypothesis testing. Examples are taken from engineering applications. Prerequisites: Math 233 or equivalent.
Credit 3 units. EN: TU

E35 ESE 330 Engineering Electromagnetics Principles
Electromagnetic theory as applied to electrical engineering: vector calculus; electrostatics and magnetostatics; Maxwell's equations, including Poynting's theorem and boundary conditions; uniform plane-wave propagation; transmission lines, TEM modes, including treatment of general lossless lines, and pulse propagation; introduction to guided waves; introduction to radiation and scattering concepts. Prerequisites: Physics 118A and ESE 318 En Math A. Corequisite: ESE 319 En Math B.
Credit 3 units. EN: TU

E35 ESE 331 Electronics Laboratory
Laboratory exercises provide students with a combination of hands-on experience in working with a variety of real instruments and in working in a simulated "virtual" laboratory setting. A sequence of lab experiments provide hands-on experience with grounding and shielding techniques, signal analysis, realistic operation amplifier (op amp) characterization, op amp based active filters characterization, MOSFET chopper/ amplifier behavior, measurement of pulses propagating on a transmission line with various terminations, experience with both AM and FM modulation. Students will gain experience in working with: sampling oscilloscopes, various signal generators, frequency counters, digital multimeters, spectrum analyzers, and contemporary connection boards. The course concludes with a hands-on project to design and demonstrate an electronic component. Prerequisites: ESE 230, ESE 232; Corequisite: ESE 330.
Credit 3 units. EN: TU

E35 ESE 332 Power, Energy and Polyphase Circuits
Fundamental concepts of power and energy; electrical measurements; physical and electrical arrangement of electrical power systems; polyphase circuit theory and calculations; principal elements of electrical systems such as transformers, rotating machines, control and protective devices, their description and characteristics; elements of industrial power system design. Prerequisite: ESE 230.
Credit 3 units. EN: TU
E35 ESE 337 Electronic Devices and Circuits

E35 ESE 351 Signals and Systems

E35 ESE 362 Computer Architecture
This course explores the interaction and design philosophy of hardware and software for digital computer systems. Topics include: Processor architecture, Instruction Set Architecture, Assembly Language, memory hierarchy design, I/O considerations, and a comparison of computer architectures. Prerequisite: CSE 260M. Same as E81 CSE 362M. Credit 3 units. EN: TU

E35 ESE 400 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. Not open to first-year or graduate students. Consult adviser. Hours and credit to be arranged. Credit variable, maximum 3 units.

E35 ESE 401 Fundamentals of Engineering Review
A review and preparation of the most recent NCEES Fundamentals of Engineering (FE) Exam specifications is offered in a classroom setting. Exam strategies will be illustrated using examples. The main topics for the review include: engineering mathematics, statics, dynamics, thermodynamics, heat transfer, mechanical design and analysis, material science and engineering economics. A discussion of the importance and responsibilities of professional engineering licensure along with ethics will be included. Same as E37 MEMS 4001 Credit 1 unit.

E35 ESE 403 Operations Research
Introduction to the mathematical aspects of various areas of operations research, with additional emphasis on problem formulation. This is a course of broad scope, emphasizing both the fundamental mathematical concepts involved, and also aspects of the translation of real-world problems to an appropriate mathematical model. Subjects to be covered include linear and integer programming, network problems, and dynamic programming. Prerequisites: CSE 131, Math 309, and ESE 326, or permission of instructor. Credit 3 units. EN: TU

E35 ESE 404 Applied Operations Research
Application of operations research techniques to real-world problems. Emphasis is given to integer linear programming and computational methods. Real-world examples of integer programs will be studied in areas such as network flow, facility location, partitioning, matching, and transportation. Special emphasis will be placed on techniques used to solve integer programs. Prerequisites: ESE 403 and CSE 131. Credit 3 units. EN: TU

E35 ESE 405 Reliability and Quality Control
An integrated analysis of reliability and quality control function in manufacturing. Statistical process control, acceptance sampling, process capability analysis, reliability prediction, design, testing, failure analysis and prevention, maintainability, availability, and safety are discussed and related. Qualitative and quantitative aspects of statistical quality control and reliability are introduced in the context of manufacturing. Prerequisite: ESE 326 or equivalent. Credit 3 units. EN: TU

E35 ESE 407 Analysis and Simulation of Discrete Event Systems
Study of the dynamic behavior of discrete event systems and techniques for analyzing and optimizing the performance of such systems. Covers both classical and recent approaches. Classical topics include Markov chains, queuing theory, networks of queues, related algorithms and simulation methods. Recent approaches include decomposition and aggregation, approximation, and perturbation analysis of nonclassical systems. Applications are drawn from various areas, including production systems. Prerequisites: Math 217, ESE 326 or equivalent, programming experience such as CSE 130 or CSE 200. Credit 3 units. EN: TU

E35 ESE 408 A System Dynamics Approach to Designing Sustainable Policies and Programs
Principles and practice of modeling dynamic systems in the sciences, engineering, social sciences and business. Model structure and its relationships to prior knowledge and assumptions, measurable quantities and ultimate use in solving problems in application areas. Problems considered are in the areas of intervention, policy making, business and engineering systems. Model verification. The basic theory and practice of system dynamics. Quantitative methods are emphasized. Senior or graduate standing. Credit 3 units. EN: TU
E35 ESE 415 Optimization
Optimization problems with and without constraints. The projection theorem. Convexity, separating hyperplane theorems; Lagrange multipliers; Kuhn-Tucker-type conditions, duality; computational procedures. Use of optimization techniques in engineering design. Prerequisites: CSE 131, Math 309 and ESE 318 or permission of instructor.
Credit 3 units. EN: TU

E35 ESE 425 Random Processes and Kalman Filtering
Probability and random variables; random processes; linear dynamic systems and random inputs; autocorrelation; spectral density; the discrete Kalman filter; applications; the extended Kalman filter for nonlinear dynamic systems. Kalman filter design using a computer package, mean square estimation; maximum likelihood; Wiener filtering and special factorization, LQG/LTR control. Prerequisite: ESE 326 and ESE 351 or equivalent.
Credit 3 units. EN: TU

E35 ESE 426 Advanced Electronic Devices
The physics of state-of-the-art electronic devices. Devices studied include novel diode structures (light-emitting diodes, semiconductor laser diodes), high-power devices (SCRs, TRIACs and power transistors), and high-speed devices. High-speed devices include heterojunction bipolar (HBT), heterojunction field-effect (HFET) and high electron mobility (HEMT) transistors used in very high-speed systems (up to 100 GHz). Advanced bipolar transistors (poly-Si), used in high-speed microprocessors, examined; also materials properties, transport mechanisms, band structure and physics of these devices. Prerequisite: ESE 336.
Credit 3 units. EN: TU

E35 ESE 427 Financial Mathematics
This course provides an accessible introduction to financial mathematics at the undergraduate level. Topics to be covered include pricing of the financial instruments such as options, forwards, futures and their derivatives along with basic hedging techniques and portfolio optimization strategies. The emphasis is put on using of discrete, mostly binary models. The general, continuous case including the concepts of Brownian motion, stochastic integral, and stochastic differential equations, is explained from intuitive and practical point of view. Among major results discussed are the Arbitrage Theorem and Black-Scholes differential equations and their solutions. Prerequisites: ESE 318 and ESE 326 or the consent of the instructor.
Credit 3 units. EN: TU

E35 ESE 429 Basic Principles of Quantum Optics and Quantum Information
This course provides an accessible introduction to quantum optics and quantum engineering for undergraduate students. This course covers the following topics: concept of photons, quantum mechanics for quantum optics, radiative transitions in atoms, lasers, photon statistics (photon counting, Sub-Poissonian photon statistics, bunching, anti-bunching, theory of photodetection, shot noise), entanglement, squeezed light, atom-photon interactions, cold atoms, atoms in cavities. The course will also provide an overview for quantum information processing: quantum computing, quantum cryptography, and teleportation. Prerequisite: Engineering Mathematics 318 or equivalent.
Credit 3 units. EN: TU

E35 ESE 433 Radio Frequency and Microwave Technology for Wireless Systems
Focus is on the components and associated techniques employed to implement analog and digital radio frequency (RF) and microwave (MW) transceivers for wireless applications, including: cell phones; pagers; wireless local area networks; global positioning satellite-based devices; and RF identification systems. A brief overview of system-level considerations is provided, including modulation and detection approaches for analog and digital systems; multi-access techniques and wireless standards; and transceiver architectures. Focus is on RF and MW: transmission lines; filter design; active component modeling; matching and biasing networks; amplifier design; and mixer design. Prerequisite: ESE 330.
Credit 3 units. EN: TU

E35 ESE 434 Solid-State Power Circuits and Applications
Study of the strategies and applications power control using solid-state semiconductor devices. Survey of generic power electronic converters. Applications to power supplies, motor drives and consumer electronics. Introduction to power diodes, thyristors and MOSFETs. Prerequisites: ESE 232, ESE 351.
Credit 3 units. EN: TU

E35 ESE 435 Electrical Energy Laboratory
Experimental studies of principles important in modern electrical energy systems. Topics include: AC power measurements, electric lighting, photovoltaic cells and arrays, batteries, DC-DC and DC-AC converters, and three-phase circuits. Each experiment requires analysis, simulation with MultiSim, and measurement via LabView and the Elvis II platform. Prerequisites: ESE 230 and ESE 351.
Credit 3 units. EN: TU

E35 ESE 436 Advanced Electronic Devices
The physics of state-of-the-art electronic devices. Devices studied include novel diode structures (light-emitting diodes, semiconductor laser diodes), high-power devices (SCRs, TRIACs and power transistors), and high-speed devices. High-speed devices include heterojunction bipolar (HBT), heterojunction field-effect (HFET) and high electron mobility (HEMT) transistors used in very high-speed systems (up to 100 GHz). Advanced bipolar transistors (poly-Si), used in high-speed microprocessors, examined; also materials properties, transport mechanisms, band structure and physics of these devices. Prerequisite: ESE 336.
Credit 3 units. EN: TU

E35 ESE 437 Sustainable Energy Systems
We will survey the field of sustainable energy and explore contributions within electrical and systems engineering. Topics include introductory electric power systems, smart grids, and the roles of heat engines, photovoltaics, wind power, and energy storage, as well as analysis and optimization of energy systems. The course will include review and discussion of literature, problem sets, exams, and student projects. Prerequisites: ESE 318 or 319 and ESE 230 or ESE 351 or permission of instructor.
Credit 3 units. EN: TU

E35 ESE 438 Applied Optics
Topics relevant to the engineering and physics of conventional as well as experimental optical systems and applications explored. Items addressed include geometrical optics, Fourier optics such as diffraction and holography, polarization and optical birefringence such as liquid crystals, and nonlinear optical phenomena and devices. Prerequisite: ESE 330 or equivalent.
Credit 3 units. EN: TU

E35 ESE 439 Introduction to Quantum Communications
This course covers the following topics: quantum optics, single-mode and two-mode quantum systems, nonlinear optics, and quantum systems theory. Specific topics include the following: Dirac notation quantum mechanics; harmonic oscillator quantization; number states, coherent states, and squeezed states; direct, homodyne, and heterodyne
design;  

E35 ESE 447 Robotics Laboratory  
Introduces the students to various concepts such as modeling, identification, model validation and control of robotic systems. The course focuses on the implementation of identification and control algorithms on a two-link robotic manipulator (the so-called pendubot) that will be used as an experimental testbed. Topics include: introduction to the mathematical modeling of robotic systems; nonlinear model, linearized model; identification of the linearized model; input-output and state-space techniques; introduction to the identification of the nonlinear model: energy-based techniques; model validation and simulation; stabilization using linear control techniques; a closer look at the dynamics; stabilization using nonlinear control techniques. Prerequisite: ESE 351 or MEMS 431. Corequisites or Prerequisites: ESE 441 and 446.  
Credit 3 units. EN: TU

E35 ESE 448 Systems Engineering Laboratory  
Experimental study of real and simulated systems and their control. Identification, input-output analysis, design and implementation of control systems. Noise effects. Design and implementation of control laws for specific engineering problems. Corequisites: ESE 441 and knowledge of a programming language.  
Credit 3 units. EN: TU

E35 ESE 449 Digital Process Control Laboratory  
Applications of digital control principles to laboratory experiments supported by a networked distributed control system. Lecture material reviews background of real-time programming, data acquisition, process dynamics, and process control. Exercises in data acquisition and feedback control design using simple and advanced control strategies. Experiments in flow, liquid level, temperature, and pressure control. Term project. Prerequisite: ESE 441 or EECE 401 or equivalent. (Prior to FL2015, this course was numbered: E63 433.) Same as E44 EECE 424.  
Credit 3 units. EN: TU

E35 ESE 455 Quantitative Methods for Systems Biology  
Application of computational mathematical techniques to problems in contemporary biology. Systems of linear ordinary differential equations in reaction-diffusion systems, hidden Markov models applied to gene discovery in DNA sequence, ordinary differential equation and stochastic models applied to gene regulation networks, negative feedback in transcription and metabolic pathway regulation. Prerequisites: (1) Math 217 Differential Equations and (2) a programming course and familiarity with MATLAB.  
Credit 3 units. EN: TU

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Credit 3 units. EN: TU

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Credit 3 units. EN: TU
state assignment, asynchronous circuits, and built-in self-test techniques. Prerequisite: CSE 260M.
Same as E81 CSE 460T
Credit 3 units. EN: TU

E35 ESE 461 Design Automation for Integrated Circuit Systems
Integrated circuit systems provide the core technology that power today’s most advanced devices and electronics: smart phones, wearable devices, autonomous robots, and cars, aerospace or medical electronics. These systems often consist of silicon microchips made up by billions of transistors and contain various components such as microprocessors, DSPs, hardware accelerators, memories, and I/O interfaces; therefore, design automation is critical to tackle the design complexity at the system level. The objectives of this course are to 1) introduce transistor-level analysis of basic digital logic circuits; 2) provide a general understanding of hardware description language (HDL) and design automation tools for very large scale integrated (VLSI) systems; 3) expose students to design automation techniques used in the best-known academic and commercial systems. Topics covered include device and circuits for digital logic circuits, digital IC design flow, logic synthesis, physical design, circuit simulation and optimization, timing analysis, power delivery network analysis. Assignments include homework, mini-projects, term paper and group project. Prerequisites: ESE 232; ESE 260.
Credit 3 units. EN: TU

E35 ESE 462 Computer Systems Design
Introduction to modern design practices, including the use of FPGA design methodologies. Students use a commercial CAE/CAD system for VHDL-based design and simulation while designing a selected computation system. Prerequisites: CSE 361S and 362M.
Same as E81 CSE 462M
Credit 3 units. EN: TU

E35 ESE 465 Digital Systems Laboratory
Hardware/software co-design; processor interfacing; procedures for reliable digital design, both combinational and sequential; understanding manufacturers’ specifications; use of test equipment. Several single-period laboratory exercises, several design projects, and application of microprocessors in digital design. One lecture and one laboratory period a week. Prerequisites: CSE 260M and CSE 361S.
Credit 3 units. EN: TU

E35 ESE 467 Embedded Computing Systems
Introduces the issues, challenges and methods for designing embedded computing systems — systems designed to serve a particular application, which incorporate the use of digital processing devices. Examples of embedded systems include PDAs, cellular phones, appliances, game consoles, automobiles and iPod. Emphasis is given to aspects of design that are distinct to embedded systems. The course examines hardware, software and system-level design. Hardware topics include microcontrollers, digital signal processors, memory hierarchy and I/O. Software issues include languages, run-time environments and program analysis. System-level topics include real-time operating systems, scheduling, power management and wireless sensor networks. Students perform a course project on a real wireless sensor network testbed. Prerequisite: CSE 361S.
Same as E81 CSE 467S
Credit 3 units. EN: TU

E35 ESE 471 Communications Theory and Systems
Introduction to the concepts of transmission of information via communication channels. Amplitude and angle modulation for the transmission of continuous-time signals. Analog-to-digital conversion and pulse code modulation. Transmission of digital data. Introduction to random signals and noise and their effects on communication. Optimum detection systems in the presence of noise. Elementary information theory. Overview of various communication technologies such as radio, television, telephone networks, data communication, satellites, optical fiber and cellular radio. Prerequisites: ESE 351 and ESE 326.
Credit 3 units. EN: TU

E35 ESE 474 Introduction to Wireless Sensor Networks
This is an introductory course on wireless sensor networks for senior undergraduate students. The course uses a combination of lecturing, reading, and discussion of research papers to help each student understand the characteristics and operations of various wireless sensor networks. Topics covered include sensor network architecture, communication protocols on Medium Access Control and Routing, sensor network operation systems, sensor data aggregation and dissemination, localization and time synchronization, energy management, and target detection and tracking using acoustic sensor networks. Prerequisite: ESE 351 (Signals and Systems).
Credit 3 units. EN: TU

E35 ESE 472 Digital Signal Processing
Credit 3 units. EN: TU

E35 ESE 482 Digital Signal Processing
Introduction to the concepts of transmission of information via communication channels. Amplitude and angle modulation for the transmission of continuous-time signals. Analog-to-digital conversion and pulse code modulation. Transmission of digital data. Introduction to random signals and noise and their effects on communication. Optimum detection systems in the presence of noise. Elementary information theory. Overview of various communication technologies such as radio, television, telephone networks, data communication, satellites, optical fiber and cellular radio. Prerequisites: ESE 351 and ESE 326.
Credit 3 units. EN: TU

E35 ESE 488 Signals and Communication Laboratory
A laboratory course designed to complement the traditional EE course offerings in signal processing and communication theory. Signals and systems fundamentals: continuous-time and discrete-time linear time-invariant systems, impulse and step response, frequency response, A/D and D/A conversion. Digital signal processing: FIR and IIR digital filter design, implementation and application of the Fast Fourier Transform. Communication theory: baseband, digital communication, amplitude modulation, frequency modulation, bandpass digital communication. Laboratory experiments involve analog and digital electronics. Computer workstations and modern computational software used extensively for system simulation and real-time signal processing. Prerequisite: ESE 351.
Credit 3 units. EN: TU

E35 ESE 497 Undergraduate Research
Undergraduate research under the supervision of a faculty member. The scope and depth of the research must be approved by the faculty member prior to enrollment. A written final report and a webpage describing the research are required.
E35 ESE 498 Electrical Engineering Capstone Design Projects
Capstone design project supervised by the course instructor. The project must use the theory, techniques, and concepts of the student's major: electrical engineering or systems science & engineering. The solution of a real technological or societal problem is carried through completely, starting from the stage of initial specification, proceeding with the application of engineering methods, and terminating with an actual solution. Collaboration with a client, typically either an engineer or supervisor from local industry or a professor or researcher in university laboratories, is encouraged. A proposal, an interim progress update, and a final report are required, each in the forms of a written document and oral presentation, as well as a webpage on the project. Weekly progress reports and meetings with the instructor are also required. Prerequisite: ESE senior standing and instructor's consent. Note: This course will meet at the scheduled time only during select weeks. If you cannot attend at that time, you may still register for the course. Credit 3 units. EN: TU

E35 ESE 499 Systems Science and Engineering Capstone Design Project
Capstone design project supervised by the course instructor. The project must use the theory, techniques, and concepts of the student's major: electrical engineering or systems science & engineering. The solution of a real technological or societal problem is carried through completely, starting from the stage of initial specification, proceeding with the application of engineering methods, and terminating with an actual solution. Collaboration with a client, typically either an engineer or supervisor from local industry or a professor or researcher in university laboratories, is encouraged. A proposal, an interim progress update, and a final report are required, each in the forms of a written document and oral presentation, as well as a webpage on the project. Weekly progress reports and meetings with the instructor are also required. Prerequisite: ESE senior standing and instructor's consent. Note: This course will meet at the scheduled time only during select weeks. If you cannot attend at that time, you may still register for the course. Credit 3 units. EN: TU

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. This course will not count toward the ESE doctoral program. Credit 3 units. EN: TU

E35 ESE 502 Mathematics of Modern Engineering II
Fourier series and Fourier integral transforms and their applications to solving some partial differential equations, heat and wave equations; complex analysis and its applications to solving real-valued problems: analytic functions and their role, Laurent series representation, complex-valued line integrals and their evaluation including the residual integration theory, conformal mappings and their applications. 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. EN: TU

E35 ESE 513 Convex Optimization and Duality Theory
Graduate introduction to convex optimization with emphasis on convex analysis and duality theory. Topics include: convex sets, convex functions, convex cones, convex conjugates, Fenchel-Moreau theorem, convex duality and biconjugation, directional derivatives, subgradients and subdifferentials, optimality conditions, ordered vector spaces, Hahn-Banach theorem, extension and separation theorems, minimax theorems, and vector and set optimization. Prerequisites: ESE 415, Math 411. 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 515 Optimization in Function Space

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 and estimation problems. We cover techniques to discretize optimal control problems, numerical methods to solve them, and their optimality conditions. We apply these results to the Model Predictive Control and Estimation of nonlinear systems. Prerequisites: ESE 551, and ESE 415 or equivalent.
Credit 3 units. EN: TU

E35 ESE 519 Convex Optimization
Credit 3 units.

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

E35 ESE 521 Random Variables and Stochastic Processes I
Mathematical foundations of probability theory, including constructions of measures, Lebesque-measure, Lebesque-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 and the Kolmogorov forward and backward equations. 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
Credit 3 units. EN: TU

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 533 Introduction to Quantum Optics
This course covers 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 551 (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, Barbital's Lemmas, 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, realizability, pole-assignment, observers and decoupling of linear dynamic systems. Prerequisite: ESE 351.

Credit 3 units. EN: TU

E35 ESE 552 Linear Dynamic Systems II

Credit 3 units. EN: TU

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

Prerequisite: ESE 551.

Credit 3 units. EN: TU

E35 ESE 554 Advanced Nonlinear Dynamic Systems
E35 ESE 557 Hybrid Dynamic Systems
Theory and analysis of hybrid dynamic systems, which is the class of systems whose state is composed of continuous-valued and discrete-valued variables. Discrete-event systems models and language descriptions. Models for hybrid systems. Conditions for existence and uniqueness. Stability and verification of hybrid systems. Optimal control of hybrid systems. Applications to cyber-physical systems and robotics. Prerequisite: ESE 551.
Credit 3 units. EN: TU

E35 ESE 559 Special Topics in Systems
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 advanced topics in the area of analog circuit synthesis and analysis. 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 (SoCs) 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, factor designs with replication, fractional factorial designs, one factor experiments, two factor full factorial design w/o replications, two factor full factorial designs with replications, general full factorial designs, introduction to queueing theory, analysis of single queues, queueing networks, operational laws, mean-value analysis, time series analysis, heavy tailed distributions, self-similar processes, long-range dependence, random number generation, analysis of simulation results, and art of data presentation. Prerequisites: CSE 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 known statistics, signal estimation and detection in noise with unknown statistics, direction finding, spatial spectrum estimation, beam forming, parametric maximum-likelihood techniques. Subspace techniques, including MUSIC and ESPRIT. Performance analysis of various algorithms. Advanced topics may include structured covariance estimation, wide-band array processing, array calibration, array processing with polarization diversity, and space-time adaptive processing (STAP). Prerequisites: ESE 520, ESE 524, linear algebra, computer programming.
Credit 3 units. EN: TU

E35 ESE 588 Quantitative Image Processing
Credit 3 units. 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.