2016-17 Bulletin

School of Engineering & Applied Science Graduate Programs

Washington University in St. Louis

Table of Contents

About This Bulletin

The graduate bulletins are the catalogs of graduate programs, degree requirements and policies of the following schools of Washington University in St. Louis: Architecture & Urban Design; Art; Arts & Sciences; and Engineering & Applied Science.

The *University College Bulletin* is the catalog of University College, the professional and continuing education division of Arts & Sciences at Washington University in St. Louis. The catalog includes programs, degree requirements, course descriptions, and pertinent university policies for students earning a degree through University College.

The 2016-17 bulletins are entirely online but may be downloaded in PDF format for printing. Individual pages may be downloaded in PDF format using the "Download This Page as a PDF" option on each page. To download a full PDF, please choose from the following:

- Architecture & Urban Design (PDF) (coming soon)
- Art (PDF) (coming soon)
- Arts & Sciences (PDF) (coming soon)
- Engineering & Applied Science (PDF) (coming soon)
- University College (undergraduate and graduate) (PDF) (coming soon)

The degree requirements and policies in the *2016-17 Bulletin* apply to students entering Washington University during the 2016-17 academic year.

Every effort is made to ensure that the information, applicable policies and other materials presented in the *Bulletin* are accurate and correct. Washington University reserves the right to make changes at any time without prior notice. Therefore, the electronic version of the *Bulletin* may change from time to time without notice. The governing document at any given time is the then-current version of the *Bulletin*, as published online, and then-currently applicable policies and information are those contained in that *Bulletin*.

For the most current information about available courses and class scheduling, visit WebSTAC (https://acadinfo.wustl.edu). Questions concerning the *Bulletin* may be addressed to bulletin_editor@wustl.edu.

For more graduate and professional programs, please visit the following websites:

- The Brown School (http://brownschool.wustl.edu)
- Olin Business School (http://olin.wustl.edu)
- School of Law (http://law.wustl.edu/academics)
- School of Medicine (http://bulletinoftheschoolofmedicine.wustl.edu)

About WUSTL

Who We Are Today

Washington University in St. Louis, a medium-sized, independent university, is dedicated to challenging its faculty and students alike to seek new knowledge and greater understanding of an ever-changing, multicultural world. The university is counted among the world's leaders in teaching and research, and draws students from all 50 states, the District of Columbia, Guam, Puerto Rico and the Virgin Islands. Students and faculty come from more than 100 countries around the world.

The university offers more than 90 programs and almost 1,500 courses leading to bachelor's, master's and doctoral degrees in a broad spectrum of traditional and interdisciplinary fields, with additional opportunities for minor concentrations and individualized programs. For more information about the university, please visit the University Facts page (http://wustl.edu/about/facts) of our website.

Enrollment by School

For enrollment information, please visit the University Facts page (http://wustl.edu/about/facts/#students) of our website.

Committed to Our Students: Mission Statement

Washington University's mission is to discover and disseminate knowledge, and protect the freedom of inquiry through research, teaching and learning. Washington University creates an environment to encourage and support an ethos of wide-ranging exploration. Washington University's faculty and staff strive to enhance the lives and livelihoods of students, the people of the greater St. Louis community, the country and the world.

Our goals are:

- to welcome students, faculty and staff from all backgrounds to create an inclusive community that is welcoming, nurturing and intellectually rigorous;
- to foster excellence in our teaching, research, scholarship and service;
- to prepare students with attitudes, skills and habits of lifelong learning and leadership thereby enabling them to be productive members of a global society; and
- to be an institution that excels by its accomplishments in our home community, St. Louis, as well as in the nation and the world.

To this end we intend:

- to judge ourselves by the most exacting standards;
- to attract people of great ability from diverse backgrounds;
- to encourage faculty and students to be bold, independent and creative thinkers;
- to provide an exemplary, respectful and responsive environment for living, teaching, learning and working for present and future generations; and
- to focus on meaningful measurable results for all of our endeavors.

Trustees & Administration

Board of Trustees

Please visit the Board of Trustees website (http://boardoftrustees.wustl.edu) for more information.

University Administration

In 1871, Washington University co-founder and then-Chancellor William Greenleaf Eliot sought a gift from Hudson E. Bridge, charter member of the university's Board of Directors, to endow the chancellorship. Soon it was renamed the "Hudson E. Bridge Chancellorship."

Led by the chancellor, the officers of the university administration are detailed on the university website (http://wustl.edu/about/leadership).

Academic Calendar

Fall Semester 2016

Date	Day	Description
August 29	Monday	Classes begin
September 5	Monday	Labor Day holiday
October 15-18	Saturday-Tuesday	Fall Break
November 23-27	Wednesday-Sunday	Thanskgiving Break
December 9	Friday	Last day of classes
December 12-14	Monday-Wednesday	Reading Days
December 15-21	Thursday-Wednesday	Final Examinations

Spring Semester 2017

Date	Day	Description
January 16	Monday	Martin Luther King Jr. holiday
January 17	Tuesday	Classes begin
March 12-18	Sunday-Saturday	Spring Break
April 28	Friday	Last day of classes
May 1-3	Monday-Wednesday	Reading Days
May 4-10	Thursday-Wednesday	Final Examinations
May 19	Friday	Commencement

Summer Semester 2017

Date	Day	Description
May 22	Monday	First Summer Session begins
May 29	Monday	Memorial Day holiday
July 4	Tuesday	Independence Day holiday
August 17	Thursday	Last Summer Session ends

Washington University recognizes the individual student's choice in observing religious holidays that occur during periods when classes are scheduled. Students are encouraged to arrange with their instructors to make up work missed as a result of religious observance, and instructors are asked to make every reasonable effort to accommodate such requests.

Campus Resources

Student Support Services

Cornerstone: The Learning Center. Located on the first floor of Gregg Residence House on the South 40, Cornerstone is the hub of academic support at Washington University. We provide undergraduate students with help in a variety of forms, including course-specific structured study groups, residential academic resources, and intensive intersession review programs in gateway courses such as chemistry and calculus. Other services include workshops on study skills, time management, and note-taking, and walk-in help desks for fundamental courses like calculus, physics and writing. Cornerstone also offers final exam work sessions and fee-based graduate and professional school entrance exam preparation courses. Additionally, Cornerstone administers TRiO, a federally funded program that offers advising, leadership development, financial assistance, and other support to undergraduate students who are low-income, the first in their family to go to college, and/or have a documented disability. On Sundays and weekday evenings, we offer flexible space where students can study, work on class projects, or relax. Most services are free, and each year, more than 2,000 students participate in one or more of our programs. For more information, visit our website (http://cornerstone.wustl.edu) or call 314-935-5970.

Disability Resources. Cornerstone is also home to Disability Resources, which assists students with disabilities and students with suspected disabilities by providing guidance and accommodations to ensure equal access to our campus, both physically and academically. Disability Resources serves both undergraduate and graduate students enrolled in the schools on the Danforth Campus. Students enrolled as students in the School of Medicine should contact their Program Director or their Program's Student Affairs staff member. Students enrolled in the Division of Biology & Biomedical Sciences (DBBS) are considered graduate students in Arts & Sciences and are served by Disability Resources. Students may visit our website (http://disability.wustl.edu) or call Cornerstone at 314-935-5970 for more information.

Office for International Students and Scholars. If a student is joining the university from a country other than the United States, this office can assist that individual through its orientation programs, by issuing certificates of eligibility (visa documents), and by offering special services for non-native English speakers in the English Language Programs. In addition, the office provides personal and cross-cultural counseling and arranges social, cultural and recreational activities that foster international understanding on campus.

The Office for International Students and Scholars is located in the Stix International House at 6470 Forsyth Boulevard. For more information, visit our website (http://oiss.wustl.edu) or call 314-935-5910.

The Writing Center. The Writing Center, a free service, offers writing advice to all Washington University undergraduate and graduate students. Tutors will read and discuss any kind of work in progress, including student papers, senior theses, application materials, dissertations, and oral presentations. The Writing Center staff is trained to work with students at any stage of the writing process, including brainstorming, developing and clarifying an argument, organizing evidence, and improving style. Rather than editing or proofreading, tutors will emphasize the process of revision and teach students how to edit their own work. Appointments are preferred and can be made online (http://writingcenter.wustl.edu).

The Writing Center is located in Olin Library on level one.

Student Health Services

Student Health Services (SHS) provides medical and mental health care for undergraduate and graduate students. Student Health Services staff members include licensed professionals in Medical Services, Mental Health Services, and Health Promotion Services. Please visit us in Dardick House on the South 40, or visit our website (http://shs.wustl.edu) for more information about each of our services and staff members.

Hours:
Monday, Tuesday and Thursday 8 a.m.-6 p.m.
Wednesday 10 a.m.-6 p.m.
Friday 8 a.m.-5 p.m.
Saturday 9 a.m.-1 p.m.

A nurse answer line is available to answer any medical questions a student may have when SHS is closed. For after-hours care, please call: 314-935-6666.

Medical Services staff members provide care for the evaluation and treatment of an illness or injury, preventive health care and health education, and nutrition, physical therapy, travel medicine and women's health services. Student Health Services' providers are considered in-network and are participating members of the Washington University in St. Louis Physician's Network. Any condition requiring specialized medical services will be referred to an appropriate community specialist. Student Health Services accepts most health insurance plans and will be able to bill the plan according to plan benefits when care is accessed at SHS. The student health insurance plan requires a referral any time care is not provided at SHS. Call 314-935-6666 or visit our website (http://shs.wustl.edu) to schedule an appointment for medical care, including allergy injections prescribed by your allergist, health consultations, for HIV or other STD testing, or for immunizations.

Appointments also are available for assessment, treatment and referral for students who are struggling with substance abuse.

The SHS pharmacy is available to all Washington University students and their dependents who participate in the student health insurance plan. The pharmacy accepts most prescription insurance plans; please check with the pharmacist to see if your prescription plan is accepted at the pharmacy.

The SHS lab provides full laboratory services. Approximately 20 tests can be performed in the SHS lab. The remainder of all testing that is ordered by SHS is completed by LabCorp. LabCorp serves as our reference lab and is on the student health insurance plan as a preferred provider. The SHS lab can collect any test ordered by our providers.

All incoming students must provide proof of immunization for two measles, mumps, rubella vaccines after the age of one year old. (A titer may be provided in lieu of the immunizations.) Meningococcal vaccine proof is required. A PPD skin test in the past six months is required for students entering the university from certain countries. This list of countries may be found on our website. We suggest all students also have Tetanus Diphtheria immunization within the past five years, Hepatitis A vaccine series, Hepatitis B vaccine series and Varicella vaccine. Medical History Forms are available online (http://shs.wustl.edu). Failure to complete the required forms will delay registration and will prevent entrance into housing assignment. Please visit our website (http://shs.wustl.edu) for complete information about requirements and deadlines.

Mental Health Services staff members work with students to resolve personal and interpersonal difficulties, including conflicts with or worry about friends or family, concerns about eating or drinking patterns, and feelings of anxiety and depression. Although some concerns are more frequent than others, students' experiences are as varied as the students themselves. Staff members help each person figure out her or his own situation. Services include individual, group and couples counseling; crisis counseling; psychiatric consultation; and referral for off-campus counseling. Call 314-935-6666 or visit our website (http://shs.wustl.edu) to schedule an appointment.

Health Promotion Services staff members provide information and resources on issues of interest to Washington University students including alcohol and other drugs, weight and body image, sexual health, sleep, and stress; customize professional health education programs for groups; and work with groups of students dedicated to educating their peers about healthy decision making. Call 314-935-7139 for more information.

Important Information About Health Insurance

Washington University has a student health fee designed to improve the health and wellness of the entire Washington University community. This fee supports health and wellness services and programs on campus. In addition, all full-time, degree-seeking Washington University students are automatically enrolled in the Student Health Insurance Plan upon completion of registration. Students may opt out of this coverage if there is proof of existing comprehensive insurance coverage. Information concerning opting out of the student health insurance plan can be found online (http://shs.wustl.edu) after June 1 of each year. Student Health Services does provide billing services to many of the major insurance companies in the United States. Specific fees and co-pays apply to students using Medical Services and Mental Health Services; these fees may be billable to your insurance plan. More information is available on our website (http://shs.wustl.edu).

Campus Security

The Washington University campus is among the most attractive in the nation and enjoys a safe, relaxed atmosphere. Your personal safety and the security of your property while on campus is a shared responsibility. Washington University has made safety and security a priority through our commitment to a full-time professional police department, use of closed circuit television, card access, good lighting, shuttle services, emergency telephones, and ongoing educational safety awareness programs. The vast majority of crimes that occur on college campuses are crimes of opportunity, which can be prevented.

The best protection against crime is an informed, alert campus community. Washington University has developed several programs to help make your experience here a safe and secure one. An extensive network of emergency telephones, including more than 200 "blue light" telephones, is connected directly to the University Police Department and can alert the police to your exact location. In addition to the regular shuttle service, an evening walking escort service or mobile Campus Circulator is available on the Danforth Campus.

The Campus2Home shuttle will provide a safe ride home for those living in four designated areas off campus — Skinker-DeBaliviere, Loop South, north of The Loop and just south of the campus — from 7:00 p.m. to 4:00 a.m. seven days a week. The shuttle leaves from both the Mallinckrodt Center and the Brookings Drive steps and takes passengers directly to the front doors of their buildings. Shuttle drivers then will wait and watch to make sure passengers get into their buildings safely.

The University Police Department is a full-service organization staffed by certified police officers who patrol the campus 24 hours a day throughout the entire year. The Police Department offers a variety of crime prevention programs including a high-security bicycle lock program, free personal-safety whistles, computer security tags, personal safety classes for women and men, property inventory services and security surveys. For more information on these programs, check out the Washington University Police Department website (http://police.wustl.edu).

In compliance with the Campus Crime Awareness and Security Act of 1990, Washington University publishes online (http://police.wustl.edu) an annual report, *Safety and Security on the Danforth Campus — A Guide for Students, Faculty and Staff*, which is available to all current and prospective students on the Danforth Campus and university employees on the Danforth, North and West campuses. To request a hard copy, contact the Washington University Police Department, Campus Box 1038, One Brookings Drive, St. Louis, MO 63130-4899, 314-935-9011.

University Policies

Washington University has various policies and procedures that govern our faculty, staff and students. Highlighted below are several key policies of the university, with which you should be familiar. Web links to key policies and procedures are available on the University Registrar's website (http://registrar.wustl.edu) and on the university's Compliance and Policies page (http://wustl.edu/policies). Please note that the policies identified on these websites and in this *Bulletin* do not represent an entire repository of university policies, as schools, offices and departments may implement policies that are not listed. In addition, policies may be amended throughout the year.

Nondiscrimination Statement

Washington University encourages and gives full consideration to all applicants for admission, financial aid and employment. The university does not discriminate in access to, or treatment or employment in, its programs and activities on the basis of race, color, age, religion, sex, sexual orientation, gender identity or expression, national origin, veteran status, disability or genetic information. Inquiries about compliance should be addressed to the university's Vice Chancellor for Human Resources, Washington University in St. Louis, Campus Box 1184, One Brookings Drive, St. Louis, MO 63130.

Policy on Discrimination and Discriminatory Harassment

Washington University is committed to having a positive learning and working environment for its students, faculty and staff. University policy prohibits discrimination on the basis of race, color, age, religion, gender, sexual orientation, gender identity or expression, national origin, veteran status, disability or genetic information. Harassment based on any of these classifications is a form of discrimination and violates university policy and will not be tolerated. In some circumstances such discriminatory harassment may also violate federal, state or local law. A copy of the Policy on Discrimination and Discriminatory Harassment (http://hr.wustl.edu/policies/Pages/DiscriminationAndDiscriminatoryHarassment.aspx) is available on the Human Resources website.

Sexual Harassment

Sexual harassment is a form of discrimination that violates university policy and will not be tolerated. It is also illegal under state and federal law. Title IX of the Education Amendments of 1972 prohibits discrimination based on sex (including sexual harassment and sexual violence) in the university's educational programs and activities. Title IX also prohibits retaliation for asserting claims of sex discrimination. The university has designated the Title IX Coordinator identified below to coordinate its compliance with and response to inquiries concerning Title IX. You may also submit a complaint or inquiry regarding Title IX by contacting the United States Department of Education's Office of Civil Rights at 400 Maryland Avenue, SW, Washington, DC 20202-1100 or by visiting the U.S. Department of Education website (http://ed.gov) or calling 800-421-3481. A copy of the Policy on Sexual Harassment (http://hr.wustl.edu/policies/pages/sexualharassment.aspx) is available on the Human Resources website.

For more information or to report a violation under either the Policy on Discrimination and Discriminatory Harassment or the Sexual Harassment policy, please contact:

Discrimination and Harassment Response Coordinators

Danforth Campus: Apryle Cotton, 314-935-8095, apryle.cotton@wustl.edu

School of Medicine Campus: Legail Chandler, 314-362-4900, legail_chandler@wustl.edu

Title IX Coordinator:

All campuses: Jessica Kennedy, 314-935-3118, jwkennedy@wustl.edu

Student Health

Drug and Alcohol Policy

Washington University is committed to maintaining a safe and healthful environment for members of the university community by promoting a drug-free environment as well as one free of the abuse of alcohol. Violations of the Washington University Drug and Alcohol Policy (http://hr.wustl.edu/policies/Pages/DrugandAlcoholPolicy.aspx) or Alcohol Service Policy (http://pages.wustl.edu/prograds/alcohol-service-policy) will be handled according to existing policies and procedures concerning the conduct of faculty, staff and students. This policy is adopted in accordance with the Drug-Free Workplace Act and the Drug-Free Schools and Communities Act.

Tobacco-Free Policy

Washington University is committed to providing a healthy, comfortable and productive work and learning environment for all students, faculty and staff. Research shows that tobacco use in general, including smoking and breathing secondhand smoke, constitutes a significant health hazard. The university strictly prohibits all smoking and other uses of tobacco products within all university buildings and on university property, at all times. A copy of our complete tobacco-free policy (http://hr.wustl.edu/policies/Pages/tobaccofreepolicy.aspx) is available on the Human Resources website.

Medical Examinations

Entering students must provide medical information to Student Health Services. This will include completion of a health history and a record of all current immunizations. The university strongly recommends appropriate vaccination for meningococcal disease.

If students fail to comply with these requirements prior to registration, they will be required to obtain vaccinations for measles, mumps and rubella at Student Health Services, if there is no evidence of immunity. They will be assessed the cost of the vaccinations. Students will be unable to complete registration for classes until all health requirements have been satisfied.

If students are unimmunized, they may be barred from classes and from all university facilities, including housing units, if in the judgment of the university their continued presence would pose a health risk to themselves or to the university community.

Medical and immunization information is to be given via the Student Health Services (http://shs.wustl.edu) website. All students who have completed the registration process should access the website and create a student profile by using their WUSTL key. Creating a student profile enables a student to securely access the medical history form. Fill out the form and follow the instructions for transmitting it to Student Health Services. Student information is treated securely and confidentially.

Student Conduct

The University Student Judicial Code addresses conduct expectations and discipline procedures for university students. The primary purpose of the behavior expectations set forth in the code is the protection of the campus community and the maintenance of an environment conducive to learning and inquiry.

Disciplinary proceedings are meant to be informal, fair and expeditious. Charges of non-serious misconduct are generally heard by the student conduct officer. With limited exceptions, serious or repeated allegations are heard by the campus-wide University Judicial Board or the University Sexual Assault Investigative Board where applicable.

Complaints against students that include allegations of sexual assault or certain complaints that include allegations of sexual harassment in violation of the Judicial Code are governed by the procedures found in the University Sexual Assault Investigative Board Policy (https://wustl.edu/about/compliance-policies/governance/usaib-procedures-complaints-sexual-assault-filed-students), which is available online or in hard copy from the Title IX Coordinator or the Judicial Administrator.

Students may be accountable to both governmental authorities and to the university for acts that constitute violations of law and the Student Code.

For a complete copy of the University Student Judicial Code, visit the university Academic Policies webpage (https://wustl.edu/about/compliance-policies/academic-policies).

Undergraduate Student Academic Integrity Policy

Effective learning, teaching and research all depend upon the ability of members of the academic community to trust one another and to trust the integrity of work that is submitted for academic credit or conducted in the wider arena of scholarly research. Such an atmosphere of mutual trust fosters the free exchange of ideas and enables all members of the community to achieve their highest potential.

In all academic work, the ideas and contributions of others must be appropriately acknowledged, and work that is presented as original must be, in fact, original. Faculty, students and administrative staff all share the responsibility of ensuring the honesty and fairness of the intellectual environment at Washington University.

Scope and Purpose

This statement on academic integrity applies to all undergraduate students at Washington University. Graduate students are governed by policies in each graduate school or division. All students are expected to adhere to the highest standards of behavior.
The purpose of the statement is twofold:

- To clarify the university's expectations with regard to undergraduate students' academic behavior, and
- To provide specific examples of dishonest conduct. The examples are only illustrative, NOT exhaustive.

Violations of this policy include, but are not limited to:

1. Plagiarism

Plagiarism consists of taking someone else's ideas, words or other types of work product and presenting them as one's own.

To avoid plagiarism, students are expected to be attentive to proper methods of documentation and acknowledgment. To avoid even the suspicion of plagiarism, a student must always:

- Enclose every quotation in quotation marks and acknowledge its source.
- Cite the source of every summary, paraphrase, abstraction or adaptation of material originally prepared by another person and any factual data that is not considered common knowledge. Include the name of author, title of work, publication information and page reference.
- Acknowledge material obtained from lectures, interviews or other oral communication by citing the source (name of the speaker, the occasion, the place and the date).
- Cite material from the internet as if it were from a traditionally published source. Follow the citation style or requirements of the instructor for whom the work is produced.

2. Cheating on an examination

A student must not receive or provide any unauthorized assistance on an examination. During an examination a student may use only materials authorized by the faculty.

3. Copying or collaborating on assignments without permission

When a student submits work with his or her name on it, this is a written statement that credit for the work belongs to that student alone. If the work was a product of collaboration, each student is expected to clearly acknowledge in writing all persons who contributed to its completion.

Unless the instructor explicitly states otherwise, it is dishonest to collaborate with others when completing any assignment or test, performing laboratory experiments, writing and/or documenting computer programs, writing papers or reports, and completing problem sets.

If the instructor allows group work in some circumstances but not others, it is the student's responsibility to understand the degree of acceptable collaboration for each assignment, and to ask for clarification if necessary.

To avoid cheating or unauthorized collaboration, a student should never:

- Use, copy or paraphrase the results of another person's work and represent that work as his or her own, regardless of the circumstances.
- Refer to, study from or copy archival files (e.g., old tests, homework, solutions manuals or backfiles) that were not approved by the instructor.
- Copy another's work, or to permit another student to copy his or her work.
- Submit work as a collaborative effort if he or she did not contribute a fair share of the effort.

4. Fabrication or falsification of data or records

It is dishonest to fabricate or falsify data in laboratory experiments, research papers or reports or in any other circumstances; to fabricate source material in a bibliography or "works cited" list; or to provide false information on a résumé or other document in connection with academic efforts. It is also dishonest to take data developed by someone else and present them as one's own.

Examples of falsification include:

- Altering information on any exam, problem set or class assignment being submitted for a re-grade.
- Altering, omitting or inventing laboratory data to submit as one's own findings. This includes copying laboratory data from another student to present as one's own; modifying data in a write-up; and providing data to another student to submit as his or her own.

5. Other forms of deceit, dishonesty or inappropriate conduct

Under no circumstances is it acceptable for a student to:

- Submit the same work, or essentially the same work, for more than one course without explicitly obtaining permission from all instructors. A student must disclose when a paper or project builds on work completed earlier in his or her academic career.
- Request an academic benefit based on false information or deception. This includes requesting an extension of time, a better grade or a recommendation from an instructor.
- Make any changes (including adding material or erasing material) on any test paper, problem set or class assignment being submitted for a re-grade.
- Willfully damage the efforts or work of other students.
- Steal, deface or damage academic facilities or materials.
- Collaborate with other students planning or engaging in any form of academic misconduct.
- Submit any academic work under someone else's name other than his or her own. This includes but is not limited to sitting for another person's exam; both parties will be held responsible.
- Engage in any other form of academic misconduct not covered here.

This list is not intended to be exhaustive. To seek clarification, students should ask the professor or teaching assistant for guidance.

Reporting Misconduct

Faculty responsibility

Faculty and instructors are strongly encouraged to report incidents of student academic misconduct to the academic integrity officer in their school or college in a timely manner, so that the incident may be handled fairly and consistently across schools and departments. Teaching assistants are expected to report instances of student misconduct to their supervising instructors. Faculty members are expected to respond to student concerns about academic dishonesty in their courses.

Student responsibility

If a student observes others violating this policy, he or she is strongly encouraged to report the misconduct to the instructor, to seek advice from the academic integrity officer of the school or college that offers the course in question, or to address the student(s) directly.

Exam proctor responsibility

Exam proctors are expected to report incidents of suspected student misconduct to the course instructor and/or the Disability Resource Center, if applicable.

Procedure

Jurisdiction

This policy covers all undergraduate students, regardless of their college of enrollment. Cases will be heard by school-specific committees according to the school in which the class is listed, not the school in which the student is enrolled. All violations and sanctions will be reported to the student's college of enrollment.

Administrative procedures

Individual undergraduate colleges and schools may design specific procedures to resolve allegations of academic misconduct by students in courses offered by that school, so long as the procedures are consistent with this policy and with the University Student Judicial Code.

Student rights and responsibilities in a hearing

A student accused of an academic integrity violation — whether by a professor, teaching/graduate assistant, academic integrity officer or student — is entitled to:

- Review the written evidence in support of the charge.
- Ask any questions.
- Offer an explanation as to what occurred.
- Present any material that would cast doubt on the correctness of the charge.
- Determination of the validity of the charge without reference to any past record of misconduct.

When responding to a charge of academic misconduct, a student may:

- Deny the charges and request a hearing in front of the appropriate academic integrity officer or committee.
- Admit the charges and request a hearing to determine sanction(s).
- Admit the charges and accept the imposition of sanctions without a hearing.
- Request a leave of absence from the university. The academic integrity matter must be resolved prior to re-enrollment.
- Request to withdraw permanently from the university with a transcript notation that there is an unresolved academic integrity matter pending.

A student has the following responsibilities in resolving the charge of academic misconduct:

- Admit or deny the charge. This will determine the course of action to be pursued.
- Provide truthful information regarding the charges. It is a Student Judicial Code violation to provide false information to the university or anyone acting on its behalf.

Sanctions

If found *not* in violation of the Academic Integrity Policy

If the charges of academic misconduct are not proven, no record of the allegation will appear on the transcript.

If found in violation of the Academic Integrity Policy

If, after a hearing, a student is found to have acted dishonestly, or if a student has admitted to the charges prior to a hearing, the school's academic integrity officer or committee may impose sanctions, including but not limited to the following:

- Issue a formal written reprimand.
- Impose educational sanctions, such as completing a workshop on plagiarism or academic ethics.
- Recommend to the instructor that the student fail the assignment. (A grade is ultimately the prerogative of the instructor.)
- Recommend to the instructor that the student fail the course.
- Recommend to the instructor that the student receive a course grade penalty less severe than failure of the course.
- Place the student on Disciplinary Probation for a specified period of time or until defined conditions are met. The probation will be noted on the student's transcript and internal record while it is in force.
- In cases serious enough to warrant suspension or expulsion from the university, refer the matter to the University Judicial Board for consideration.

Additional educational sanctions may be imposed. This list is not intended to be exhaustive.

Withdrawing from the course will not prevent the academic integrity officer or hearing panel from adjudicating the case, imposing sanctions or recommending grade penalties, including a failing grade in the course.

A copy of the sanction letter will be placed in the student's academic file.

Appeals

If a student believes the academic integrity officer or the committee did not conduct a fair hearing, or if a student believes the sanction imposed for misconduct is excessive, he or she may appeal to the University Judicial Board within 14 days of the original decision. Appeals are governed by Section VII C of the University Student Judicial Code.

Records

Administrative record-keeping responsibilities

It is the responsibility of the academic integrity officer in each school to keep accurate, confidential records concerning academic integrity violations. When a student has been found to have acted dishonestly, a letter summarizing the allegation, the outcome and the sanction shall be placed in the student's official file in the office of the school or college in which the student is enrolled.

Additionally, each school's academic integrity officer shall make a report of the outcome of every formal accusation of student academic misconduct to the Director of University Judicial Programs, who shall maintain a record of each incident.

Multiple offenses

When a student is formally accused of academic misconduct and a hearing is to be held by an academic integrity officer, a committee, or the University Judicial Board, the person in charge of administering the hearing shall query the director of Judicial Programs about the student(s) accused of misconduct. The director shall provide any information in his or her records concerning that student to the integrity officer. Such information will be used in determining sanctions ONLY if the student is found to have acted dishonestly in the present case. Evidence of past misconduct may not be used to resolve the issue of whether a student has acted dishonestly in a subsequent case.

Reports to faculty and student body

School and college academic integrity officers are encouraged to make periodic (at least annual) reports to the students and faculty of their school concerning accusations of academic misconduct and the outcomes, without disclosing specific information that would allow identification of the student(s) involved.

Graduate Student Academic Integrity Policies

For graduate student academic integrity policies, please refer to each individual graduate school.

Statement of Intent to Graduate

Students are required to file an Intent to Graduate at WebSTAC (https://acadinfo.wustl.edu) prior to the semester in which they intend to graduate. Additional information is available in the dean's offices of each school and in the Office of the University Registrar (http://registrar.wustl.edu).

Student Academic Records and Transcripts

The Family Educational Rights and Privacy Act of 1974 (FERPA) — Title 20 of the United States Code, Section 1232g, as amended — provides current and former students of the university with specific rights of access to and control over their student record information. In compliance with the statute, appropriate federal regulations and guidelines recommended by the American Association of Collegiate Registrars and Admissions Officers, the university has adopted procedures that implement these rights.

A copy of the university policies regarding educational records and the release of student record information is available from the Office of the University Registrar (http://registrar.wustl.edu) and the university website (http://www.wustl.edu).

Transcript requests may be submitted to the Office of the University Registrar through WebSTAC. Instructions and additional information are available on the University Registrar website (http://registrar.wustl.edu).

University Affiliations

Washington University is accredited by the Higher Learning Commission (http://ncahlc.org) (800-621-7440). Washington University is a member of the Association of American Universities, the American Council on Education, the College Board, and the Independent Colleges and Universities of Missouri.

The College of Arts & Sciences is a member of the Center for Academic Integrity and the American Association of College Registrars.

The College of Architecture was one of the eight founding members of the Association of Collegiate Schools of Architecture (ACSA) in 1912.

The Graduate School is a founding member of both the Association of Graduate Schools and the Council of Graduate Schools.

The Graduate School of Architecture & Urban Design's Master of Architecture degree is accredited by the National Architectural Accreditation Board (NAAB).

The Sam Fox School of Visual Arts & Design (Art) is a founding member of, and is accredited by, the National Association of Schools of Art and Design (NASAD).

The Olin Business School is a charter member of the Association to Advance Collegiate Schools of Business International (1921) (AACSB).

In the School of Engineering & Applied Science, many of the professional degrees are accredited by the Engineering Accreditation Commission of ABET (http://abet.org).

University College is a member of the University Professional and Continuing Education Association. Business-related programs in University College are not accredited by the Association to Advance Collegiate Schools of Business (AACSB International).

The School of Law is accredited by the American Bar Association. The School of Law is a member of the Association of American Law Schools, the American Society of Comparative Law, and the Clinical Legal Education Association.

The School of Medicine is a member of the Liaison Committee on Medical Education.

The Brown School at Washington University is accredited by the Council on Social Work Education and the Council on Education for Public Health.

The University Libraries are a member of the Association of Research Libraries.

The Mildred Lane Kemper Art Museum is nationally accredited by the American Alliance of Museums.

Engineering & Applied Science

The School of Engineering & Applied Science offers programs of instruction and research leading to specified master's degrees and doctoral degrees.

Both full-time and part-time students may pursue most of the graduate programs offered by Engineering. A few graduate programs are designed primarily for full-time students. However, numerous locally employed engineers, scientists and technical managers have earned master's degrees through part-time study. Many evening graduate courses are offered, and many other graduate courses are taught during the late afternoon. Students who are employed full-time and are interested in investigating the possibility of doctoral graduate work should consult directly with the director of the particular department or program in which they are interested.

Contact Information

School of Engineering & Applied Science
Lopata Hall, Suite 204
Washington University in St. Louis
Campus Box 1220
One Brookings Drive
St. Louis, MO 63130-4899
314-935-7974
Website: http://engineering.wustl.edu
Email: gradadmissions@seas.wustl.edu

Doctoral Degrees

PhD

The PhD is not only an exploration of the knowledge in a given discipline but also an original contribution to it. To the extent that doctoral education has been successful, the student's relationship to learning is significantly changed. Having made a discovery, developed an insight, tested a theory, or designed an application, the PhD recipient is no longer a student but a colleague of the faculty. It is for this reason that the PhD is the highest degree offered by a university.

The core mission of PhD programs at research universities is to educate the future faculty of other research universities and institutions of higher education. Graduates of Washington University participate in research and teaching; they also make valuable contributions to society by applying the analytical and creative skills required for scholarship to careers in business, government, and nonprofit sectors. The Graduate School therefore works with other university offices to ensure that students have the opportunity to develop these transferable skills.

Among the critical components the university provides for these purposes are a small and select graduate student body, faculty members dedicated to scholarly work, and the physical facilities needed for research. In these regards Washington University compares favorably to the finest graduate institutions in the world. But the key ingredients of PhD completion must be provided by the student: a love of learning and a desire to increase the sum of human knowledge. Motivation and perseverance are prerequisites for success in PhD programs.

DSc

A DSc is a doctorate in science equivalent to a PhD doctoral degree. The departments of Electrical & Systems Engineering and Mechanical Engineering & Materials Science offer both the PhD and DSc doctoral options for graduate students. For more information about the differences between the PhD and DSc degrees, please refer to the Doctor of Science (DSc) section of the MEMS website (http://mems.wustl.edu/graduate/programs/Pages/default.aspx).

Academic Information

Doctoral Students

Candidates for doctoral degrees should consult their advisers to determine if there are any special regulations or requirements in effect in their particular departments or programs.

Engineering-based doctoral degrees require a minimum of 72 units. The doctoral program requires 36-48 units of course work and 24-36 units of research. The specific distribution decisions are made by the individual programs and departments.

The doctorate can be awarded only to those students whose knowledge of their field of specialization meets contemporary standards. Hence, course work completed more than seven years prior to the date the degree is awarded generally cannot be accepted as satisfying degree requirements. All requirements for the degree must be completed within seven years from the time the student is admitted to the doctoral program.

The doctoral degree has a residency requirement of one year. To satisfy the requirement, the student must devote full time for two consecutive semesters to academically relevant activities on the Washington University campus. A limited amount of outside employment may be permitted, but only with the approval of the department or program chairman and/or the Dean. Candidates for the Doctor of Philosophy degree are required to follow the guidelines of the Graduate School. Please refer to the Graduate School website (http://graduateschool.wustl.edu) for policies and guidelines for the Doctor of Philosophy degree. Candidates for the Doctor of Science degree are required to follow the guidelines of the School of Engineering & Applied Science (SEAS). Please refer to the Doctor of Science (DSc) section of our website (http://mems.wustl.edu/graduate/programs/Pages/default.aspx) for more information about the DSc requirements.

Adviser & Doctoral Committee

Once admitted to graduate standing, each doctoral student will have an adviser appointed by the chair or director of the designated area of specialization. It is the responsibility of the adviser to help the student plan a graduate program.

After the student completes a maximum of 24 units of course work, the chair will appoint a doctoral committee for the student, with the student's adviser normally serving as chair of the committee. The doctoral committee will include at least three members of the Engineering regular faculty. The committee will advise the student on course work and research and must approve the proposed program.

Doctoral Qualifying Examination

To be admitted to a candidacy for the doctoral degree, a student must pass a comprehensive qualifying examination consisting of both written and oral portions. The written portion of the examination is administered by the student's department or program, and students should consult their adviser for information concerning the scope of the examination and the dates on which it is given. Students passing the written portion of the examination are eligible to take the oral portion. The examining panel for the oral portion will consist of the student's doctoral committee, plus additional members recommended by the student's doctoral committee and approved by the department chair or program director. The panel will have a minimum of five to six members, representing two or more departments at Washington University.

Doctoral Dissertation

The candidate must defend the dissertation during a final oral examination by an examining committee to be nominated by the adviser and approved by the appropriate dean. Doctor of Philosophy candidates will have their committees approved by the Dean of the Graduate School. The committee normally consists of five to six Washington University faculty representing two or more departments in the Engineering school and requires the approval of the department chair or program director.

Doctor of Philosophy candidates should refer to the Doctoral Dissertation Guide (http://graduateschool.wustl.edu/policies-and-guides) found on the Graduate School website for specific information on preparing their dissertation for submission. Other Engineering doctoral students should prepare their dissertation according to the DSc & Master's Thesis Format Guidelines (https://engineering.wustl.edu/current-students/student-services/Pages/forms.aspx#thesis-submission) found on the Engineering website.

Each candidate for the doctoral degree must electronically submit a final approved .pdf version of his or her dissertation. The dissertation should include an abstract embodying the principal findings of the research and approved by the doctoral committee as ready for publication. Such abstract will be published in Dissertation Abstracts, which announces the availability of the dissertation for distribution.

Master's Degrees

Master of Engineering versus Master of Science Degrees

Master of Engineering degrees are typically viewed as terminal degrees allowing maximum flexibility in course selection. Master of Science degrees are more structured in terms of required course work, and students with undergraduate degrees specifically in engineering are often better prepared to enter these master's programs. Graduates from Master of Science programs are better prepared to move forward to doctoral programs, as they often become more involved in research experience. However, Master of Science programs also include course only options for those not interested in doing research.

There are different ways to earn a master's degree at Washington University:

- There are a number of Engineering disciplines that admit students to pursue a terminal master's degree. In some programs both the course option and thesis option are available. The course option may be of particular interest to part-time students who, because of their employment, might find it more convenient than the thesis requirement.
- Undergraduate students at Washington University may apply for the BS/Master's or AB/Master's program in Engineering, in which graduation with a BS or AB is followed by one year of graduate study leading to the MS degree. This option is described in the Combined Majors and/or Multiple Degrees (http://bulletin.wustl.edu/undergrad/engineering) section of this *Bulletin*.
- Students who have not previously earned a master's degree in the same field as their PhD may earn the Master of Science (MS) on the way to their PhD. This option is available in some disciplines but not in all of them.
- Students who have not previously earned a master's degree in the same field as their PhD may be awarded an MS for work done in a PhD program that they are leaving without completing. This option is available in some disciplines but not in all of them.

ELP English Placement Exams: These exams (http://oiss.wustl.edu/english-language-programs/testing/schedule) are taken by new international graduate students (in any graduate degree program) upon arrival. Students may be placed into Engr 510A or Engr 510B, courses customized to the needs of Engineering students and offered only in the spring.

Academic Information

Candidates for the master's degrees should note that in most MS programs both the thesis option and the course option are available. The course option may be of particular interest to part-time students who, because of their employment, might find it more convenient than the thesis requirement. All candidates for the master's degrees should consult with their adviser to determine the option they will follow.

All requirements for the master's degrees must be completed within six years from the time the student is admitted to graduate standing. A maximum of six units of graduate credit obtained at institutions other than Washington University may be applied toward the master's degree awarded by Engineering. Transfer credit must be recommended and approved by the department chair or program director and adviser, as well as by the Engineering Registrar. No courses carrying grades lower than B can be accepted for transfer credit.

For the thesis option, a minimum of 24 units of course work and a minimum of 6 units of research are required. The student must also write a satisfactory thesis prepared under the supervision of a member of the Engineering faculty. Candidates for master's degrees under the course option must submit a minimum of 30 units of approved graduate course credit. A department may have additional requirements beyond the above stated minimum requirement. Students should consult with their adviser as several master's degrees require more than 30 graduate units.

To earn more than one master's degree from Engineering, the student's final program of course work for each such master's degree must include a minimum of 15 units of preapproved courses not included as part of the final program of course work for any other master's degree awarded by Engineering.

Master's Thesis

A candidate for the degree Master of Science (thesis option) should prepare his or her thesis according to the Master's Thesis Format Guidelines (http://engineering.wustl.edu/current-students/student-services/Pages/forms.aspx) found on the Engineering website.

The candidate's department chair or program director will appoint a thesis committee of three faculty members, with the student's adviser as chair, who will read the thesis and judge its acceptability. At some point, as per published deadlines, the candidate will then deliver a draft copy of the thesis to the Engineering Student Services Office for format approval. Three copies of the final thesis accepted by the committee and approved for format must be delivered to the Engineering Student Services Office no later than the deadline stated in the online academic calendar. In addition, prior to submission of the final hard copies, the student must submit the document electronically to Washington University Open Scholarship (http://openscholarship.wustl.edu/cgi/ir_submit.cgi?context=eng_etds).

Master's Final Examinations

The final examination for the Master of Science candidates under the thesis option consists of an oral examination conducted by the thesis committee and any additional faculty members that the department or program chairman may wish to designate. At this examination the candidate will present and defend the thesis.

Candidates for the Master of Science under the course option may be required to pass a final examination. The form of this examination is determined by the faculty of the area of specialization, and students should consult their advisers, department chairs, or program directors for details concerning this examination.

Fields of Study

Biomedical Engineering

Modern biomedical engineers face a far different world than those trained even two decades ago. Explosive advances in our ability to probe and understand molecular and cellular processes and their interconnections now make it imperative that the powers of engineering be brought to bear at ever smaller, as well as at systemwide, levels. This will not only produce new discoveries at the most fundamental levels but also accelerate the translation of these discoveries into practical applications.

Our vision is that future leaders and lasting impact will arise from successfully integrating engineering concepts and approaches across molecular to whole body levels. Moreover, those also trained to integrate the analytical, modeling and systems approaches of engineering with the complex, and sometimes overwhelming, descriptive details of biology will be uniquely positioned to address new and exciting opportunities. We are committed to educating and training the next generation of biomedical engineers with this vision in mind. Consequently, we have leveraged our existing strengths to build our department around the five research programs representing some of the most exciting frontiers: Biomaterials/Tissue Engineering; Cardiovascular Engineering; Imaging; Molecular, Cellular and Systems Engineering; and Neural Engineering. These areas provide exciting training opportunities for students with a variety of backgrounds and interests.

Students seeking the **Master of Science (MS) in Biomedical Engineering** will need to complete 30 credits of course work which includes a core curriculum. MS students pursuing the thesis option perform research on a topic approved by a sponsoring faculty member. Results of the study are published in a thesis that is defended in front of a committee of faculty members prior to graduation. The results are also expected to be published as a paper in a peer-reviewed journal. A total of 30 credits can be completed in 2-4 semesters.

Students seeking the **Master of Engineering (MEng) in Biomedical Innovation** will complete an immersive 12-month medical technology entrepreneurial experience culminating in their own intellectual property intended to be spun out into commercial endeavors following graduation. A total of 30 credits of course work is required.

Students seeking the **PhD in Biomedical Engineering** focus on five overlapping research programs that represent frontier areas of biomedical engineering and leverage the existing strengths of our current faculty and resources. Our core and more than 90 affiliated faculty work together in a number of interdisciplinary research centers and pathways offering students the opportunity to work in a diverse and rich spectrum of BME research areas. The **MD/PhD in Biomedical Engineering,** given jointly with the top-ranked School of Medicine, gives students in-depth training in modern biomedical research and clinical medicine. The typical MD/PhD career combines patient care and biomedical research but leans toward research.

Email:	bme@seas.wustl.edu
Website:	https://bme.wustl.edu

Faculty

Chair

Steven C. George (https://engineering.wustl.edu/Profiles/Pages/Steven-George.aspx)
Elvera and William Stuckenberg Professor and Chair
MD, University of Missouri
PhD, University of Washington in Seattle
Tissue engineering; microphysiological systems; vascularizing engineered tissues

Endowed Professors

Rohit V. Pappu (https://engineering.wustl.edu/Profiles/Pages/Rohit-Pappu.aspx)
Edwin H. Murty Professor of Engineering
PhD, Tufts University
Macromolecular self assembly and function; computational biophysics

Yoram Rudy (https://engineering.wustl.edu/Profiles/Pages/Yoram-Rudy.aspx)
Fred Saigh Distinguished Professor of Engineering
PhD, Case Western Reserve University
Cardiac electrophysiology; modeling of the cardiac system

Lori A. Setton (https://engineering.wustl.edu/Profiles/Pages/Lori-Setton.aspx)
Lucy and Stanley Lopata Distinguished Professor of Biomedical Engineering
PhD, Columbia University
Biomaterials for local drug delivery; tissue regenerations specific to the knee joints and spine

Larry A. Taber (https://engineering.wustl.edu/Profiles/Pages/Larry-Taber.aspx)
Dennis and Barbara Kessler Professor of Biomedical Engineering
PhD, Stanford University
Mechanics of growth and development; cardiac mechanics

Lihong Wang (https://engineering.wustl.edu/Profiles/Pages/Lihong-Wang.aspx)
Gene K. Beare Distinguished Professor of Biomedical Engineering
PhD, Rice University
Biophotonics and multimodality optical imaging

Frank Yin (https://engineering.wustl.edu/Profiles/Pages/Frank-Yin.aspx)
Stephen F. and Camilla T. Brauer Distinguished Professor of Biomedical Engineering
MD, PhD, University of California, San Diego
Tissue and cell biomechanics; hemodynamics

Professors

Mark Anastasio (https://engineering.wustl.edu/Profiles/Pages/Mark-Anastasio.aspx)
PhD, University of Chicago
Imaging sciences; phase-contrast; x-ray imaging

Jianmin Cui (https://engineering.wustl.edu/Profiles/Pages/Jianmin-Cui.aspx)
PhD, State University of New York–Stony Brook
Ion channels; channel structure-function relationship; biophysics

Daniel Moran (https://engineering.wustl.edu/Profiles/Pages/Daniel-Moran.aspx)
PhD, Arizona State University
Motor control; neural engineering; neuroprosthetics; movement biomechanics

Quing Zhu
PhD, University of Pennsylvania
Biophotonics and multimodality ultrasound and optical imaging

Associate Professors

Dennis L. Barbour (https://engineering.wustl.edu/Profiles/Pages/Dennis-Barbour.aspx)
MD, PhD, Johns Hopkins University
Auditory physiology; sensory cortex neurocircuitry; novel perceptual diagnostics and therapeutics

Vitaly Klyachko (https://engineering.wustl.edu/Profiles/Pages/Vitaly-Klyachko.aspx)
PhD, University of Wisconsin-Madison
Synaptic function and plasticity; neural circuits; information analysis; neurological disorders

Baranidharan Raman (https://engineering.wustl.edu/Profiles/Pages/Barani-Raman.aspx)
PhD, Texas A&M University
Computational and systems neuroscience; neuromorphic engineering; pattern recognition; sensor-based machine olfaction

Jin-Yu Shao (https://engineering.wustl.edu/Profiles/Pages/Jin-Yu-Shao.aspx)
PhD, Duke University
Cell mechanics; receptor and ligand interactions; molecular biomechanics

Kurt A. Thoroughman (https://engineering.wustl.edu/Profiles/Pages/Kurt-Thoroughman.aspx)
PhD, Johns Hopkins University
Human motor control and motor learning; neural computation

Assistant Professors

Jan Bieschke (https://engineering.wustl.edu/Profiles/Pages/Jan-Bieschke.aspx)
PhD, Max Planck Institute for Biophysical Chemistry/University of Braunschweig
Single molecule fluorescence and other biophysical methods to probe the mechanistic underpinnings of protein misfolding

Hong Chen (https://engineering.wustl.edu/Profiles/Pages/Hong-Chen.aspx)
PhD, University of Washington
Physical acoustics; therapeutic ultrasound and ultrasound imaging

Kristen Naegle (https://engineering.wustl.edu/Profiles/Pages/Kristen-Naegle.aspx)
PhD, Massachusetts Institute of Technology
Computational systems biology with emphasis on cellular networks involved in cancer and diabetes

Jon Silva (https://engineering.wustl.edu/Profiles/Pages/Jonathan-Silva.aspx)
PhD, Washington University
Ion channel biophysics

Lecturer

Patricia Widder
MS, Washington University

Degree Requirements

Please refer to the following sections for information about the:

- Master of Science (MS) (p. 16)
- Master of Engineering (MEng) (p. 16)
- Doctor of Philosophy (PhD) and Combined MD/PhD (p. 17)

The Master of Science (MS) in Biomedical Engineering

A core curriculum that must be satisfied by all graduate MS students consists of the following:

- Two graduate-level courses in life sciences
- One graduate-level course in mathematics
- One graduate-level course in computer science
- Three BME courses from the approved course list

Please visit the Biomedical Engineering (BME) website (http://bme.wustl.edu/graduate/ms/Pages/default.aspx) for a comprehensive list of the approved and core courses.

Candidates for the MS must accumulate a total of 30 graduate course credits beyond the bachelor's degree. Only 6 of the 30 graduate course credits may be transferred from another university. There are two options: thesis and non-thesis.

Thesis option

For this option, a minimum of 24 credits of course work is required, with the balance being thesis research. The courses must fulfill the core curriculum requirement (courses found on BME website (http://bme.wustl.edu/graduate/ms/Pages/default.aspx)).

The remainder of the course work is generally driven by the student's research interest. Upon completion of the thesis, the candidate must pass an oral defense conducted by his or her thesis committee. This will consist of a public presentation followed by questions from the committee. Candidates must have a cumulative grade point average of 2.7 or better to receive the degree.

Non-Thesis option

Candidates must accumulate a total of 30 graduate credits, have a cumulative grade point average of 2.7 or better, and satisfy the core curriculum requirements. The balance of the course credits should be selected with a view toward coherence reflecting a specialization in a research area.

Graduate-level courses given by other departments and schools may be substituted for courses in the approved list with the permission of the director of master's studies. The full list of core and approved courses can be found on the BME website (http://bme.wustl.edu/graduate/ms/Pages/default.aspx)*.*

The Master of Engineering (MEng) in Biomedical Innovation

This 12-month professional graduate degree is designed for students interested in entrepreneurship or "intra"preneurship for advanced placement within a medical device company or running their own startup. It is a team-based approach in which students develop the engineering, manufacturing and business skills to solve an unmet clinical need.

The program consists of 30 units that are distributed into five areas:

- Engineering Skills (6 units)
- Master Design (10 units)
- Biomedical Project Development (4 units)
- Biomedical Business Development (4 units)
- Targeted Electives (6 units)

The Master of Engineering program has a list of specific courses that are required. These are found in the course section in the E62 BME 57## sequence. Visit the BME website (http://bme.wustl.edu/graduate/meng/Pages/default.aspx) for the MEng program timeline.

PhD and Combined MD/PhD in Biomedical Engineering

The department offers programs leading to the doctor of philosophy (PhD) in Biomedical Engineering and combined MD/PhD degrees. The latter degree is given jointly with the School of Medicine.

The doctoral degree requires a minimum of 72 credits beyond the bachelor's level, with a minimum of 36 being course credits (including the core curriculum) and a minimum of 24 credits of doctoral dissertation research.

The core curriculum that must be satisfied by all PhD students consists of the following:

- One graduate-level course in life sciences
- One graduate-level course in mathematics
- One graduate-level course in computer science or exemption by proficiency
- Four BME courses from an approved list

Please visit the Biomedical Engineering (BME) website (https://bme.wustl.edu/graduate/phd/Pages/default.aspx) for a comprehensive list of the approved and core curriculum courses.

The core requirements represent 6-7 courses, with a total of 9 graduate courses required for the PhD. Up to 9 units of BME 601C Research Rotation (https://courses.wustl.edu/CourseInfo.aspx?sch=E&dept=E62&crs=601C) and/or BME 501C Graduate Seminar (https://courses.wustl.edu/CourseInfo.aspx?sch=E&dept=E62&crs=501C) may be counted toward the 36 units of graduate course work required for the PhD. Up to two 400-level courses may be counted toward the 9 courses of graduate course work required for the PhD (not including independent study courses, journal clubs or seminar-based courses). Graduate courses may be transferred in (up to 24 units) but must be evaluated and approved by the Director of Doctoral Studies. The evaluation and approval may occur at any time but course transfer does not become official until after one year in residence at Washington University.

Students seeking the **PhD in Biomedical Engineering** enroll in two to three courses each semester and participate in two or three laboratory rotations in the first year. At the end of that year, they take their oral qualifying exam consisting of a 15-20 minute presentation of their research done to date in the mentor's laboratory followed by an oral exam addressing any issues directly related to their rotation report or their oral presentation. Upon successfully passing the qualifying examination, they advance to candidacy and complete the balance of their requirements. During the second and third years, students complete their remaining courses, perform their one-semester teaching assistantship, and begin their thesis research. By the end of the third year, students must complete their thesis proposal. Students must also complete one accepted first author publication and complete a dissertation.

Students pursuing the combined **MD/PhD in Biomedical Engineering** must complete the degree requirements for both schools. MD/PhD students typically complete the first two years of the medical school pre-clinical curriculum while also performing one or more research rotations, then the remaining requirements for the doctoral degree, and finally the clinical training years of the medical degree. The department generally gives graduate course credits for some of the medical school courses toward fulfillment of course requirements for the PhD degree. This is arranged on an individual basis between the student, his or her academic adviser, and the director of graduate studies.

Courses

Below are all BME graduate-level courses. Visit https://courses.wustl.edu to view semester offerings for E62 BME (https://courses.wustl.edu/CourseInfo.aspx?sch=E&dept=E62&crslvl=5:8).

E62 BME 501C BME Doctoral Seminar Series
This is a one-unit credit option for BME students who attend regularly scheduled BME seminars (or approved substitute seminars). A satisfactory grade is obtained by submission of a two-page peer-reviewed paper written by one of the regularly scheduled BME seminar speakers whose seminar the student attended. Papers are to be submitted to the Graduate Student Administrator for review by the Director of Doctoral Studies. Prerequisites: Students must be current BME students in their second year and beyond in order to register.
Credit 1 unit.

E62 BME 503A Cell and Organ Systems Biology
This 1.5-semester course integrates and extends the basic principles of cell biology and physiology to the functions of the major organ systems of the body, i.e., muscle, cardiovascular, renal, respiratory, gastrointestinal and endocrine. Same as M75 503, offered through the medical school. This course is open to biomedical engineering students only. Permission must be

obtained by the chairman in Biomedical Engineering. Starts at same time as Medical School classes and ends the middle of spring semester.
Credit 6 units.

E62 BME 506 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 E35 ESE 596
Credit 1 unit.

E62 BME 524 Tissue Engineering
This course integrates the principles and methods of engineering and life sciences toward the fundamental understanding of normal and pathological mammalian tissues especially as they relate to the development of biological substitutes to restore, or improve tissue function. Current concepts and strategies including drug delivery, tissue and cell transplantation, and in vivo tissue regeneration are introduced as well as their respective clinical applications. Prerequisites: BME 366; or MEMS 3410, Biol 2960 and 2970; or permission of the instructor.
Credit 3 units. EN: TU

E62 BME 527 Design of Artificial Organs
Medical devices that replace the function of one of the major organs in the body must usually interface with flowing blood. Examples include total artificial hearts, left ventricular assist devices, membrane oxygenators, hemodialysis systems and encapsulated endocrine cells. The design of these devices relies on integration of knowledge from a variety of fields, in particular computational fluid dynamics and blood rheology. We study the process by which a concept for a device eventually leads to a functioning, blood-contacting medical device, with most of the focus on the design of left ventricular assist devices. Students learn to use CAD to design blood pumping devices, test their designs via computational fluid dynamics, and 3-D print and test their pumps with water. Prerequisite: BME 366 or equivalent course in Transport Phenomena (including momentum and mass transfer).
Credit 3 units. EN: TU

E62 BME 528 Translational Regenerative Medicine
This course provides students with an opportunity to connect basic research with applications in translation for several tissues/disease models. Course sessions will alternate between literature on basic mechanisms of development/stem cell biology and applications led by researchers or clinicians working in each area. Areas of focus will include cardiovascular development/congenital heart disease and arrhythmia, lung, endocrinology/diabetes, gut/intestinal disorders, musculoskeletal, neural (peripheral and brain), liver, hematology and eye. Emphasis on how discovery can be translated will be a major focus of the course. Students will be expected to review and present on primary literature in the field. Graduate standing is required. Prerequisites: graduate standing Engineering or DBBS.
Credit 3 units.

E62 BME 530A Molecular Cell Biology for Engineers
This course is designed for upper-level undergraduates and first-year graduate students with a background in engineering. This course covers the biology of cells of higher organisms: protein structure and function; cellular membranes and organelles; cell growth and oncogenic transformation; cellular transport, receptors and cell signaling; the cytoskeleton, the extracellular matrix and cell movement. Emphasis is placed on examples relevant to biomedical engineering. The course includes two lectures per week and one discussion section. In the discussion section, the emphasis is on experimental techniques used in cell biology and the critical analysis for primary literature. Note this course does not count for engineering topics credits and is meant to fulfill a life science requirement for engineering or physical sciences graduate students. Prerequisites: Biol 2960 and 2970 or graduate standing.
Credit 4 units.

E62 BME 537 Computational Molecular Biology
This course focuses on mathematical and algorithmic issues in systems biology and biological sequence analysis. The essential mathematics is introduced first. Systems biology topics include synthetic biology, dynamical systems modeling, mapping and modeling gene regulatory networks, constraint based approaches to predictive modeling of metabolic networks, and the integration of regulatory and metabolic models. Sequence analysis topics include, Hidden Markov Models, parameter inference, sequence alignment and modeling transcription factor binding sites. This course includes a combination of paper and pencil homework assignments and programming labs. Prerequisites: an introductory course in computer programming or equivalent experience and at least two semesters of calculus.
Credit 3 units. EN: TU

E62 BME 538 Cell Signal Transduction
This class covers the elements of cell signal transduction important to human development, homeostasis and disease. Lectures are combined with primary literature review to cover canonical signaling and current topics within the field. Spatial, time and dose-dependent aspects of signaling are of particular focus. Topics include: G protein-coupled receptors, receptor tyrosine kinases, adhesion signaling, the MAPK cascade, lipid signaling, the DNA damage response, and autocrine, paracrine and juxtacrine signaling. Prerequisites: BME 530A or BME 5068.
Credit 3 units.

E62 BME 550 Numerical Methods for Computational Modeling in Biomedicine
Advanced computational methods are required for the creation of biological models. Students will be introduced to the process of model development from beginning to end, which includes model formulation, how to solve and parameterize equations, and how to evaluate model success. To illustrate the potential of these methods, participants will systematically build a model to simulate a "real-life" biological system that is applicable to their research or interest. A mechanistic appreciation of the methods will be gained by programming the methods in a low-level language (C++) in a Linux environment. While extensive programming knowledge is not required, participants are likely to find that some programming background will be helpful. Students enrolled in the 550 graduate class will be required to complete a final project that incorporates the methods taught in class.

Prerequisites: introductory programming course similar to E81 CSE 131.
Same as E62 BME 450
Credit 3 units. EN: TU

E62 BME 5565 Mechanobiology of Cells and Matrices
At the interface of the cell and the extracellular matrix, mechanical forces regulate key cellular and molecular events that profoundly affect aspects of human health and disease. This course offers a detailed review of biomechanical inputs that drive cell behavior in physically diverse matrices. In particular, cytoskeletal force-generation machineries, mechanical roles of cell-cell and cell-matrix adhesions, and regulation of matrix deformations are discussed. Also covered are key methods for mechanical measurements and mathematical modeling of cellular response. Implications of matrix-dependent cell motility in cancer metastasis and embryonic development are discussed. Prerequisite: graduate standing or permission of the instructor.
Same as E37 MEMS 5565
Credit 3 units. EN: TU

E62 BME 559 Intermediate Biomechanics
This course covers several of the fundamental theories of solid mechanics that are needed to solve problems in biomechanics. The theories of nonlinear elasticity, viscoelasticity and poroelasticity are applied to a large range of biological tissues including bone, articular cartilage, blood vessels, the heart, skeletal muscle and red blood cells. Other topics include muscle activation, the biomechanics of development and functional adaptation, and the mechanics of hearing. Prerequisites: BME 240 and ESE 317 (or ESE 318 or 319) or equivalent, or permission of instructor.
Credit 3 units. EN: TU

E62 BME 5610 Protein Structures and Dynamics
This course covers the concepts and methods involved in the analysis of protein structure, stability, folding and misfolding. Topics include protein structural elements, amyloid structure, intra- and intermolecular forces, folding pathways and intermediates, phi-value analysis, kinetics of protein folding and of amyloid formation, and their application to problems of bioengineering and biophysics. Two-thirds of the course will consist of lectures; the other third will be student seminars, in which each student presents a paper from primary literature and its concept and methodology that is discussed in detail. Prerequisites: BME 320B Bioengineering Thermodynamics or equivalent.
Same as E62 BME 461
Credit 3 units. EN: TU

E62 BME 562 Mechanics of Growth and Development
This course applies the fundamental principles of solid mechanics to problems involving growth, remodeling and morphogenesis of cells, tissues and organs. Introduction to developmental biology, nonlinear elasticity, viscoelasticity and active contraction. Particular topics include cellular morphogenetic mechanisms, growth and development of the cardiovascular system, and adaptive remodeling of bone. Prerequisites: BME 240 or MEMS 241 or equivalent.
Credit 3 units. EN: TU

E62 BME 564 Orthopaedic Biomechanics — Cartilage/ Tendon
Basic and advanced viscoelasticity and finite strain analysis applied to the musculoskeletal system, with a primary focus on soft orthopaedic tissues (cartilage, tendon and ligament). Topics include: mechanical properties of cartilage, tendon and ligament; applied viscoelasticity theory for cartilage, tendon and ligament; cartilage, tendon and ligament biology; tendon and ligament wound healing; osteoarthritis. This class is geared to graduate students and upper-level undergraduates familiar with statics and mechanics of deformable bodies. Prerequisite: BME 240 or equivalent. *Note*: BME 590Z (BME 463/563) Orthopaedic Biomechanics — Bones and Joints is *not* a prerequisite.
Same as E37 MEMS 5564
Credit 3 units. EN: TU

E62 BME 565 Biosolid Mechanics
Introduction to the mechanical behaviors of biological tissues of musculoskeletal, cardiac and vascular systems. Topics to be covered include static force analysis and nonlinear optimization theory; linearly elastic models for stress-strain analysis and solutions to relevant problems in bioelasticity; models of active structures (e.g., muscles); strain energy methods and nonlinear tissue behaviors; and introductory theory for finite element analysis. Emphasis will be placed on modeling stress-strain relations with relevance to biological tissues. Prerequisites: BME 240 or equivalent and ESE 318 and ESE 319.
Same as E62 BME 465
Credit 3 units. EN: TU

E62 BME 5702 Application of Advanced Engineering Skills for Biomedical Innovators
Students will work in small teams to apply core engineering skills covered in BME 5701 such as FEM, CAD, microcontroller programming, circuit design, data informatics, and app development to particular clinical needs or processes chosen by the instructing staff. Prerequisites: BME 5701 or permission of instructor.
Credit 3 units.

E62 BME 5711 Ideation of Biomedical Problems and Solutions
This course is part one of the year-long master's design sequence for the BME Master of Engineering. The course will begin with a boot camp primer of HIPAA certification, clinical etiquette, medical law, and intellectual property law. This will be followed by a rotation period of guided shadowing of clinicians. Following each rotation, students will review and present their findings, with a view toward problem solving and project generation. Three-fourths of the way through the course, students will form into teams, choose a master's project, and begin intensive study of their chosen problem or process. The final weeks of the course will focus on problem scope and definition, identification of creative alternatives, and consultation with experts in the field. Prerequisite: acceptance into the Master of Engineering program.
Credit 3 units.

E62 BME 5712 Implementation of Biomedical Solutions
This course is part two of the year-long master's design sequence for the BME Master's of Engineering. Students will work in small groups to begin to design a solution to the problem identified in BME 5711. Options and alternatives will

be evaluated and a best-choice solution will be chosen, based on an in-depth study of constraints upon the problem, including engineering materials, economic, safety, social, manufacturing, ethical, sustainability, and other requirements. Core skills such as FEM, CAD, circuit design, microcontroller programming, and 3-D printing will be applied to create first an alpha mockup for proof of concept, followed by a full working prototype by the end of the semester. Prerequisites: BME 5711 or permission of instructor.
Credit 3 units.

E62 BME 5713 Translation of Biomedical Solutions to Products
This course is the third and final part of the year-long master's design course sequence. Through a repeated sequence of iteration, fabrication and verification, design teams will refine and optimize their master's design project, bringing it to completion. Prerequisites: BME 5712 or permission of instructor.
Credit 4 units.

E62 BME 572 Biological Neural Computation
This course considers the computations performed by the biological nervous system with a particular focus on neural circuits and population-level encoding/decoding. Topics include Hodgkin-Huxley equations; phase-plane analysis; reduction of Hodgkin-Huxley equations; models of neural circuits; plasticity and learning; and pattern recognition and machine learning algorithms for analyzing neural data. Note: Graduate students in psychology or neuroscience who are in the Cognitive, Computational and Systems Neuroscience curriculum pathway may register in Biol 5657 for three credits. For non-BME majors, conceptual understanding, and selection/application of right neural data analysis technique are stressed. Hence homework assignments/examinations for the two sections are different, however all students are required to participate in a semester-long independent project as part of the course. Prerequisites: Calculus, Differential Equations, Basic Probability and Linear Algebra undergraduates need permission of the instructor. Biol 5657 prerequisites: permission from the instructor.
Credit 3 units. EN: TU

E62 BME 5722 Feasibility Evaluation of Biomedical Products
TBD. Prerequisites: MEng program.
Credit 2 units.

E62 BME 5731 Business Foundations for Biomedical Innovators
For medical innovators, a successful translation from product to market will require careful strategy and an understanding of the steps needed to form and fund a biotech business, either as a new startup or as an extension of the product line of an existing company. This course will provide a first look at the steps in this process, including intellectual property concerns, R&D, clinical strategy, regulatory issues, quality management, reimbursement, marketing strategy, sales and distribution, operating plans, and approaches to funding. Prerequisites: MEng program.
Credit 2 units.

E62 BME 5732 Entrepreneurship for Biomedical Innovators
This course will apply the concepts covered in BME 5731 in an interactive process that will provide practical experience. Topics of intellectual property, R&D, clinical strategy, regulatory issues, quality management, reimbursement, marketing strategy, sales and distribution, operating plans, and approaches to funding will be covered. Along with practical exercises, access to specialists and experts in these topics from the St. Louis entrepreneurial community will be provided as an integral part of the course. Prerequisite: MEng program.
Credit 2 units.

E62 BME 574 Quantitative Bioelectricity and Cardiac Excitation
Action potential generation, action potential propagation, source-field relationships in homogeneous and inhomogeneous media, models of cardiac excitation and arrhythmia, quantitative electrocardiography. Prerequisites: differential equations, Laplace transform, electromagnetic field theory (undergraduate level).
Credit 3 units. EN: TU

E62 BME 575 Molecular Basis of Bioelectrical Excitation
Ion channels are the molecular basis of membrane excitability in all cell types, including neuronal, heart and muscle cells. This course presents the structure and the mechanism of function of ion channels at the molecular level. It introduces the basic principles and methods in the ion channel study as well as the structure-function relation of various types of channels. Exemplary channels that have been best studied are discussed to illustrate the current understanding. Prerequisites: knowledge of differential equations, electrical circuits and chemical kinetics.
Credit 3 units.

E62 BME 5771 Biomedical Product Development
Advances in science and technology have opened the health care field to innovation now more than any other time in history. Engineers and inventors can make real and rapid improvements to patient treatments, length of hospital stay, procedure time, cost containment, and accessibility to treatment. However, a successful transition from idea to implementation requires careful market analysis and strategy planning. This course will address the steps in this process, including personal and team strength assessment, medical need validation, brainstorming initial solutions, market analysis, solution evaluation, regulatory, patent and intellectual property concerns, manufacturability, risk assessment and mitigation, and global considerations. Students will be expected to review resource material prior to coming to class in order to facilitate active class discussion and team-based application of the material during class; regular attendance will be key to course success. The course will focus on applying product development techniques to several real unmet medical needs; students will thus perform analysis and create reports and presentations for several different product solutions. Peer and faculty evaluations will provide feedback to improve individual technique. In addition, throughout the semester, local biomedical entrepreneurs will visit to share their expertise and experiences. Prerequisites: graduate or professional student standing or permission of the instructor.
Credit variable, maximum 3 units.

E62 BME 5772 Biomedical Business Development
For medical innovators, a successful translation from product to market will require careful strategy and an understanding of the steps needed to form and fund a biotech business, either as a new startup or as an extension of the product line of an existing company. This course will address the steps in this process, including intellectual property concerns, R&D, clinical strategy, regulatory issues, quality management, reimbursement,

marketing strategy, sales and distribution, operating plans, and approaches to funding. Prerequisites: graduate or professional student standing or permission of the instructor.
Credit 3 units.

E62 BME 5799 Independent Study for Candidates in the Master of Engineering Program
Independent investigation on a topic of special interest. The student and mentor must justify the requested number of units. The MEng Program Director must approve the requested number of units.
Credit variable, maximum 6 units.

E62 BME 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.
Same as E35 ESE 589
Credit 3 units. EN: TU

E62 BME 5901 Integrative Cardiac Electrophysiology
Quantitative electrophysiology of the heart, integrating from the molecular level (ion channels, regulatory pathways, cell signaling) to the cardiac cell (action potential and calcium transient), multicellular tissue (cell-cell communication) and the whole heart. Prerequisite: permission of instructor.
Credit 3 units. EN: TU

E62 BME 5902 Cellular Neurophysiology
This course examines the biophysical concepts of synaptic function with the focus on the mechanisms of neural signal processing at synapses and elementary circuits. The course combines lectures and discussion sessions of primary research papers. Topics include synaptic and dendritic structure, electrical properties of axons and dendrites, synaptic transmission, rapid and long-term forms of synaptic plasticity, information analysis by synapses and basic neuronal circuits, principles of information coding, mechanisms of learning and memory, function of synapses in sensory systems, models of synaptic disease states such as Parkinson and Alzheimer's diseases. Additionally, a set of lectures is devoted to modern electrophysiological and imaging techniques, and modeling approaches to study synapses and neural circuits. Prerequisite: senior or graduate standing.
Credit 3 units. EN: TU

E62 BME 5903 Physical Methods for Biomedical Scientists
The course will introduce the spectrum of biophysical techniques used in biomedical sciences with a focus on advanced fluorescence spectroscopy. The first half of the course (January to spring break) will introduce the concepts behind techniques such as: dynamic light scattering, SPR, analytical ultracentrifugation size-exclusion and affinity chromatography, atomic force microscopy, fluorescence spectroscopy, FRET, FTIR, circular dichroism, fluorescence correlation spectroscopy, sub-diffraction microscopy. The second half of the course will be held as six 3 h block lab classes (Fridays 10 a.m.-1 p.m.) in which the students will use these techniques in experiments on protein folding, protein stability and amyloid formation. Prior attendance of BME 461 Protein Structure and Dynamics is encouraged. Because of limited room in the experimental lab, attendance will be limited to nine students. Prerequisite: senior or graduate standing.
Same as E62 BME 4903
Credit 3 units. EN: TU

E62 BME 5911 Cardiovascular Biophysics Journal Club
This journal club is intended for beginning graduate students, advanced undergraduates and MSTP students with a background in the quantitative sciences (engineering, physics, math, chemistry, etc.). The subjects covered are inherently multidisciplinary. We review landmark and recent publications in quantitative cardiovascular physiology, mathematical modeling of physiologic systems and related topics such as chaos theory and nonlinear dynamics of biological systems. Familiarity with calculus, differential equations and basic engineering/thermodynamic principles is assumed. Knowledge of anatomy/physiology is optional.
Credit 1 unit.

E62 BME 5913 Molecular Systems Biology: Computation & Measurements for Understanding Cell Physiology and Disease
Systems-level measurements of molecules in cells and tissues harbor the promise to identify the ways in which tissues develop, maintain, age, and become diseased. This class will introduce the systems-level measurement techniques for capturing molecular information and the mathematical and computational methods for harnessing the information from these measurements to improve our understanding of cell physiology and disease. This is a practical class, which involves implementation of the concepts in MATLAB and will be applied to existing, real data from published journal articles. Molecular topics will include: gene expression, microRNA, proteins, post-translational modifications, drugs, and splicing. Computational/mathematical topics covered will include: statistical inference, dimensionality reduction techniques, unsupervised and supervised machine learning, and graph-based techniques. Prerequisites: A working knowledge of molecular biology, linear algebra, and statistics is required.
Credit 3 units. EN: TU

E62 BME 593 Computational Methods for Inverse Problems
Inverse problems are ubiquitous in science and engineering, and form the basis for modern imaging methods. This course will introduce students to the mathematical formulation of inverse problems and modern computational methods employed to solve them. Specific topics covered will include regularization theory, compressive sampling, and a survey of relevant numerical optimization methods. The application of these methods to tomographic imaging problems will be addressed in detail. Prerequisites: ESE 318, 319, 326, 351.
Same as E62 BME 493
Credit 3 units. EN: TU

E62 BME 594 Ultrasound Imaging
Introduce basic principles of ultrasound imaging, diagnostic ultrasound imaging systems, clinical applications, and emerging technologies in industry. Prerequisites: ESE 318, 319, 351.
Same as E62 BME 494
Credit 3 units. EN: TU

E62 BME 599 Master's Research
Credit variable, maximum 6 units.

E62 BME 600 Doctoral Research
Credit variable, maximum 12 units.

E62 BME 601 Research Rotation for BME Doctoral Students

E62 BME 601C Research Rotation for BME Doctoral Students
Credit 3 units.

E62 BME 602 Teaching Assistantship - Basic
This is a pass/fail course for the fulfillment of the basic teaching requirement which is required for the PhD degree. A form obtained from the BME department must be submitted to the instructor at the end of the semester for approval in order to receive a grade.

E62 BME 603 Teaching Assistantship - Advanced
This is a pass/fail course for the fulfillment of the advanced teaching requirement which is required for the PhD degree. A form obtained from the BME department must be submitted to their thesis mentor upon completion of requirements for approval in order to receive a grade.

E62 BME 883 Master's Continuing Student Status

Computer Science & Engineering

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

Master's Programs

The Department of Computer Science & Engineering offers three master's degrees: **Master of Science in Computer Science**, **Master of Science in Computer Engineering**, and **Master of Engineering in Computer Science & Engineering**. We accept both full-time and part-time students offering class schedules that are flexible enough for a part-time student but provide enough classes for students to attend full-time. Obtaining a master's degree from the Department of Computer Science & Engineering can be done as a pure course-option (MS degrees only) or can incorporate a specialized research experience. Master's research is a great way for our students to easily transition into future doctoral studies. Graduates of our program are also prepared to enter the industry with many accepting positions at companies like Boeing, Google and Microsoft.

PhD Programs

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

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

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

Faculty

Chair

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

Endowed Professors

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

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

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

Professors

Jeremy Buhler (https://engineering.wustl.edu/Profiles/Pages/Jeremy-Buhler.aspx)
PhD, Washington University
Computational biology, genomics, algorithms for comparing and annotating large biosequences

Shantanu Chakrabartty (https://engineering.wustl.edu/Profiles/Pages/Shantanu-Chakrabartty.aspx)
PhD, Johns Hopkins University
Analog computing techniques, self-powered sensors, floating-gate circuits, biosensors and bioelectronics

Roger D. Chamberlain (https://engineering.wustl.edu/Profiles/Pages/Roger-Chamberlain.aspx)
DSc, Washington University
Computer engineering, parallel computation, computer architecture, multiprocessor systems

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

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

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

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

Raj Jain (https://engineering.wustl.edu/Profiles/Pages/Raj-Jain.aspx)
PhD, Harvard University
Wireless networks, network security, next generation internet, sensor networks, telecommunications networks, performance analysis, traffic management, quality of service

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

Robert Pless (https://engineering.wustl.edu/Profiles/Pages/Robert-Pless.aspx)
PhD, University of Maryland
Computer vision, medical imaging, sensor network algorithms, citizen science

Weixiong Zhang (https://engineering.wustl.edu/Profiles/Pages/Weixiong-Zhang.aspx)
PhD, University of California, Los Angeles
Computational biology, genomics, machine learning and data mining, and combinatorial optimization

Associate Endowed Professor

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

Associate Professors

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

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

Viktor Gruev (https://engineering.wustl.edu/Profiles/Pages/Viktor-Gruev.aspx)
PhD, Johns Hopkins University
Low power integrated sensory systems, integrated polarization imaging, focal plane spatiotemporal image sensors, current mode image sensors, sensory systems in 3-D fabrication technology, micro/nano fabrication, micro fluidics, and low power analog/digital integrated circuits

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

Assistant Professors

Yasutaka Furukawa (https://engineering.wustl.edu/Profiles/Pages/Yasutaka-Furukawa.aspx)
PhD, University of Illinois at Urbana-Champaign
Computer vision and computer graphics

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

Brendan Juba (https://engineering.wustl.edu/Profiles/Pages/Brendan-Juba.aspx)
PhD, Massachusetts Institute of Technology
Theoretical approaches to artificial intelligence founded on computational complexity theory and theoretical computer science more broadly construed

Angelina Lee (https://engineering.wustl.edu/Profiles/Pages/I-Ting-Angelina-Lee.aspx)
PhD, Massachusetts Institute of Technology
Designing linguistics for parallel programming, developing runtime system support for multithreaded software, and building novel mechanisms in operating systems and hardware to efficiently support parallel abstractions

Benjamin Moseley (https://engineering.wustl.edu/Profiles/Pages/Ben-Moseley.aspx)
PhD, University of Illinois at Urbana-Champaign
Design and analysis of algorithms, online and approximation algorithms, parallel computing, large data analysis, green computing and algorithmic applications

Research Faculty

Sharlee Climer
PhD, Washington University
Computational biology, artificial intelligence, mathematical modeling, combinatorial optimization, pattern recognition

Lecturers

Ruth Miller
PhD, University of Houston
Data mining, database, bioinformatics

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

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

Todd Sproull (http://research.engineering.wustl.edu/%7Etodd)
PhD, Washington University
Computer networking and mobile application development

Senior Professors

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

Mark A. Franklin
Hugo F. and Ina Champ Urbauer Professor of Engineering
PhD, Carnegie Mellon University
Computer architecture, systems analysis and parallel processing, storage systems design

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

Professors Emeriti

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

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

Degree Requirements

Please refer to the following sections for information about the:

- MS in Computer Science (p. 25)
- MS in Computer Engineering (p. 25)
- MEng in Computer Science and Engineering (p. 25)
- Certificate in Data Mining and Machine Learning (p. 26)
- PhD in Computer Science or Computer Engineering (p. 26)

MS in Computer Science

The MS in Computer Science is directed toward students with a computer science background who are looking for a program and course work that is more software-focused. It can be either a pure course option program, or it can incorporate either a project or a thesis. If a student chooses a degree option that incorporates a research experience, this MS degree may provide a solid stepping stone to future doctoral studies.

Course Option

This option requires 30 units of graduate credit (all of which must be taken for a grade of C- or better). Students must also follow the general degree requirements listed below and complete the breadth requirements.

Thesis/Project Option

The thesis or project options require 24 units of graduate credit (all of which must be taken for a grade of C- or better) in addition to 6 units of either thesis or project courses (CSE 599 or CSE 598 respectively). Students pursuing the project option may opt to take 27 units of graduate courses and only 3 units of CSE 598 with adviser approval. Students must also follow the general degree requirements listed below. Thesis students are exempt from the breadth requirements.

General Degree Requirements

- 18 of the 30 units must be departmental courses at the 500-level or above.
- With departmental approval, up to 12 units may be taken from outside of the department. Such approval shall be contingent on the credits being suitably technical graduate-level content.To count more than 6 units from outside the CSE department, an appropriate justification for the additional increment shall be provided by the adviser and student. Departmental approval shall be evaluated with increasing stringency for each additional increment.
- Up to 9 units of 400-level courses can count for graduate credit.
- None of of the 30 units may be taken as independent study (i.e., CSE 400 or CSE 500).
- Courses with an "N" designation do not count toward the master's degree.
- Breadth Requirements (required of the course and project options) which include one 500-level Theoretical Computer Science (T) course, one 500-level Software Systems (S) course, and one 500-level Machine and Architecture (M) course.
- As per Engineering School guidelines, students must maintain a GPA of at least 2.70.

MS in Computer Engineering

The MS in Computer Engineering is best suited for students who are looking to focus more on computer engineering (hardware) aspects. Like the MS in Computer Science, the MS in Computer Engineering program can be either a pure course option program, or it can incorporate either a project or a thesis. If appropriate research experiences are included in the degree option, this can can also lead toward future doctoral studies.

Course Option

This option requires 30 units of graduate credit (all of which must be taken for a grade of C- or better). Students must also follow the general degree requirements listed below.

Thesis/Project Option

The thesis or project options require 24 units of graduate credit (all of which must be taken for a grade of C- or better) in addition to 6 units of either thesis or project courses (CSE 599 or CSE 598 respectively). Students must also follow the general degree requirements listed below.

General Degree Requirements

- 18 of the 30 units must be from the designated graduate-level Computer Engineering courses. Please visit our website (http://cse.wustl.edu/graduateprograms/Pages/ms-in-computer-engineering.aspx) for a comprehensive list.
- In addition to the non-CSE courses on the list of designated graduate-level Computer Engineering courses, up to 12 additional units may be taken from outside the department. Such approval shall be contingent on the credits being suitably technical graduate-level content.To count more than 6 units from outside the CSE department, an appropriate justification for the additional increment shall be provided by the adviser and student. Departmental approval shall be evaluated with increasing stringency for each additional increment.
- Up to 9 units of 400-level courses can count for graduate credit.
- None of of the 30 units may be taken as independent study (i.e., CSE 400 or CSE 500).
- Courses with an "N" designation do not count toward the master's degree.
- As per Engineering School guidelines, students must maintain a GPA of at least 2.70.

MEng in Computer Science and Engineering

The MEng in Computer Science and Engineering is specifically designed for students who would like to combine studies in computer science and computer engineering, possibly in conjunction with graduate-level work in another discipline, or for other reasons need a more flexible structure to their master's studies. The MEng offers more flexibility by allowing for approved outside courses (i.e., courses not specifically taken in computer science, such as various business courses) to count toward the degree; in this manner, an MEng student can customize his or her program, incorporating interdisciplinary components when/if approved by the faculty adviser. Work in the program culminates in a capstone project highlighting each student's ambitions, interests, and accomplishments in the program. MEng students typically move directly into the industry.

Degree Requirements

- The MEng requires 30 total units including 24 units of graduate-level course work (all of which must be taken for a grade of C- or better) and 6 units of CSE 598 Master's Project culminating in a successful project defense.
- 12 of the remaining 24 units must be departmental courses at the 400 level or above. Of these 12 units, 9 units must be at the 500 level.
- With departmental approval, up to 12 units may be taken from outside of the department. Such approval shall be contingent on the credits being suitably technical graduate-level content. To count more than 6 units from outside the CSE department, an appropriate justification for the additional increment shall be provided by the adviser and student. Departmental approval shall be evaluated with increasing stringency for each additional increment.
- Up to 15 units of 400-level courses can count for graduate credit.
- None of the 30 units may be taken as independent study (i.e., CSE 400 or CSE 500).
- Courses with an "N" designation do not count toward the master's degree.
- As per Engineering School guidelines, students must maintain a GPA of at least 2.70.

The Certificate in Data Mining and Machine Learning

The Certificate in Data Mining and Machine Learning can be awarded in conjunction with any engineering master's degree. In order to qualify for this certificate, students enrolled in any master's in engineering program will need to meet the requirements listed below in addition to the standards requirements for their master's degree.

Required Courses

CSE 417T	Introduction to Machine Learning	3
CSE 517A	Machine Learning	3
CSE 541T	Advanced Algorithms	3

Foundations Courses

Choose two:

CSE 511A	Introduction to Artificial Intelligence	3
CSE 513T	Theory of Artificial Intelligence and Machine Learning	3
CSE 514A	Data Mining	3
CSE 515T	Bayesian Methods in Machine Learning	3
CSE 519T	Advanced Machine Learning	3
Math 493	Probability	3
Math 494	Mathematical Statistics	3

Applications Courses

Choose one:

CSE 427S	Cloud Computing with Big Data Applications	3
CSE 516A	Multi-Agent Systems	3
CSE 559A	Computer Vision	3
CSE 584A	Algorithms for Biosequence Comparison	3
CSE 587A	Algorithms for Computational Biology	3

Please Note

- All courses must be taken for a grade.
- Students with previous courses in machine learning may place out of CSE 417T. These students will be required to complete an additional foundations course for a total of three foundations courses.
- Students who began the certificate prior to FL16 who have successfully completed 517A independent of 417T will be required to complete an additional foundations course in place of 417T for a total of three foundations courses. No student will be allowed to take 417T after the successful completion of 517A.
- Any student who began the certificate prior to FL16 may choose to take 441T in place of 541T.

PhD in Computer Science or Computer Engineering

Students can choose to pursue a PhD in Computer Science or Computer Engineering. The requirements vary for each degree. Here are the core requirements:

- Complete 72 units of regular courses (at least 33 units), seminars (at least 3 units), and research credits (at least 24 units), including 9 units of breadth requirements for both the PhD in Computer Science and Computer Engineering degrees.
- Satisfy fundamental teaching requirements by acting as a teacher or course TA, pedagogical teaching requirements by completing a certain number of qualifying pedagogy workshops, and scholarly communication requirements by participating in the Doctoral Student Research Seminar.
- Pass milestones demonstrating abilities to understand research literature, communicate orally and in writing,

and formulate a detailed research plan. These milestones include an oral qualifying examination, a portfolio review for admission to candidacy, and a dissertation proposal defense, culminating in a dissertation defense.

For more information, please refer to the Doctoral Program Guide on our website (http://cse.wustl.edu/graduateprograms/Pages/doctoral-program-guide.aspx).

Courses

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

E81 CSE 500 Independent Study
Credit variable, maximum 3 units.

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

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

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

E81 CSE 506M Principle and Methods of Micro- and Nanofabrication
A hands-on introduction to the fundamentals of micro- and nanofabrication processes with emphasis on cleanroom practices. The physical principles of oxidation, optical lithography, thin film deposition, etching and metrology methods will be discussed, demonstrated and practiced. Students will be trained in cleanroom concepts and safety protocols. Sequential microfabrication processes involved in the manufacture of microelectronic and photonic devices will be shown. Training in imaging and characterization of micro- and nanostructures will be provided. Prerequisites: graduate or senior standing or permission of the instructor.
Same as E37 MEMS 5611
Credit 3 units. EN: TU

E81 CSE 507A Technology Entrepreneurship
This is a course for students who plan to be, or work with, entrepreneurs. An entrepreneurial mindset is needed to create or grow economically viable enterprises, be they new companies, new groups within companies, or new university laboratories. This course aims to cultivate an entrepreneurial perspective with particular emphasis on information technology-related activities. The course is jointly offered for business and CSE students, allowing for acculturation between these disciplines. In addition to an introductory treatment of business and technology fundamentals, course topics include: business ethics, opportunity assessment, team formation, financing, intellectual property and university technology transfer. The course features significant participant and guest instruction from experienced practitioners. Prerequisites: none.
Credit 3 units.

E81 CSE 511A Introduction to Artificial Intelligence
The discipline of artificial intelligence (AI) is concerned with building systems that think and act like humans or rationally on some absolute scale. This course is an introduction to the field, with special emphasis on sound modern methods. The topics include knowledge representation, problem solving via search, game playing, logical and probabilistic reasoning, planning, dynamic programming, and reinforcement learning. Programming exercises concretize the key methods. The course targets graduate students and advanced undergraduates. Evaluation is based on written and programming assignments, a midterm exam and a final exam. Prerequisites: CSE 347, ESE 326, Math 233.
Credit 3 units.

E81 CSE 512A Statistical Computing for Scientific Research
Provides students a solid understanding of statical computing issues that concern empirical researchers in different sciences. Topics covered include: computer architecture, Monte Carlo simulation, bootstrapping and jackknifing, nonparametric smoothing, and Markov chain Monte Carlo methods. Prerequisite: basic statistics or permission of the instructor. Students are assumed to be familiar with: basic calculus, probability, regression, MLE theory and simple programming.
Credit 3 units.

E81 CSE 513T Theory of Artificial Intelligence and Machine Learning
Mathematical foundations for Artificial Intelligence and Machine Learning. An introduction to the PAC-Semantics ("Probably Approximately Correct") as a common semantics for knowledge obtained from learning and declarative sources, and the computational problems underlying the acquisition and processing of such knowledge. We emphasize the design and analysis of efficient algorithms for these problems, and examine for which representations these problems are known or believed to be tractable. Prerequisite: CSE 347.
Credit 3 units. EN: TU

E81 CSE 514A Data Mining
With the vast advancement in science and technology, data acquisition in large quantities are routinely done in many fields. Examples of large data include various types of data on the internet, high-throughput sequencing data in biology and medicine, extraterrestrial data from telescopes in astronomy, and images from surveillance cameras in security. Mining a large amount of data through data mining has become an effective means to extracting knowledge from data. This course introduces the basic concepts and methods for data mining and provides hands-on experience for processing, analyzing and modeling structured and unstructured data. Homework problems, exams and programming assignments will be administrated throughout the course to enhance learning. Prerequisites: CSE 247 and ESE 326 (or Math 320) or their equivalent, or permission of the instructor.
Credit 3 units. EN: TU

E81 CSE 515T Bayesian Methods in Machine Learning
This course will cover machine learning from a Bayesian probabilistic perspective. Bayesian probability allows us to model and reason about all types of uncertainty. The result is a powerful, consistent framework for approaching many problems that arise in machine learning, including parameter estimation, model comparison, and decision making. We will begin with a high-level introduction to Bayesian inference, then proceed to cover more-advanced topics. These will include inference techniques (exact, MAP, sampling methods, the Laplace approximation, etc.), Bayesian decision theory, Bayesian model comparison, Bayesian nonparametrics, and Bayesian optimization. Prerequisites: CSE 417T, ESE 326.
Credit 3 units. EN: TU

E81 CSE 516A Multi-Agent Systems
This course introduces the fundamental techniques and concepts needed to study multi-agent systems, in which multiple autonomous entities with different information sets and goals interact. We will study algorithmic, mathematical, and game-theoretic foundations, and how these foundations can help us understand and design systems ranging from robot teams to online markets to social computing platforms. Topics covered may include game theory, distributed optimization, multi-agent learning and decision-making, preference elicitation and aggregation, mechanism design, and incentives in social computing systems. Prerequisites: CSE 247, ESE 326 and Math 233.
Credit 3 units. EN: TU

E81 CSE 517A Machine Learning
This course assumes a basic understanding of machine learning and covers advanced topics at the frontier of the field in-depth. Topics to be covered include kernel methods (support vector machines, Gaussian processes), neural networks (deep learning), and unsupervised learning. Depending on developments in the field, the course will also cover some advanced topics, which may include learning from structured data, active learning, and practical machine learning (feature selection, dimensionality reduction). Prerequisites: CSE 247, CSE 417T, ESE 326, Math 233 and Math 309. The instructor will hold a take-home placement exam (on basic mathematical knowledge) for all students currently enrolled and on the waitlist. The exam will be due on the first day of class. Only students who pass the placement exam will be enrolled in the course.
Credit 3 units. EN: TU

E81 CSE 519T Advanced Machine Learning
This course provides a close look at advanced machine learning algorithms — their theoretical guarantees (computational learning theory) and tricks to make them work in practice. In addition, this course focuses on more specialized learning settings, including unsupervised learning, semi-supervised learning, domain adaptation, multi-task learning, structured prediction, metric learning and learning of data representations. Learning approaches may include graphical models, non-parametric Bayesian statistics, and technical topics such as sampling, approximate inference and non-linear function optimization. Mathematical maturity and general familiarity of machine learning is required. Prerequisites: CSE 517A or 511A or 7100.
Credit 3 units. EN: TU

E81 CSE 520S Real-Time Systems
This course covers software systems and network technologies for real-time applications such as automobiles, avionics, industrial automation and Internet of Things. Topics include real-time scheduling, real-time operating systems and middleware, Quality of Service, industrial networks and real-time cloud computing. Prerequisite: CSE 422S.
Credit 3 units. EN: TU

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

E81 CSE 522S Advanced Operating Systems
This course explores core OS abstractions, mechanisms and policies and how they impact support for general purpose, embedded and real-time operating environments. How

to evaluate, modify and optimize the use of kernel-level resources is covered hands-on and in detail, including CPU and I/O scheduling, memory management, and interprocess communication. Prerequisite: CSE 422S.
Credit 3 units. EN: TU

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

E81 CSE 528S Software Project Management
An introduction to the issues and basic methods used in managing software development projects. The course includes factors affecting software projects, lifecycle models, project scheduling, size and staffing, progress tracking, software metrics, managing people, and crisis management. The course includes lectures, hands-on training in selected project management tools, and case studies. In addition, each student plans and manages a simulated software project. The course is designed to familiarize software engineers and computer scientists to the issues and problems involved in managing software projects. Prerequisite: CSE 436S, significant industrial software development, or permission of instructor.
Credit 3 units.

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

E81 CSE 531S Theory of Compiling and Language Translation
Algorithms and intermediate representations for automatic program analysis are examined, with an emphasis on practical methods and efficient engineering of program optimization and transformations. The course includes a thorough treatment of monotone data flow frameworks: a mathematical model in which most optimization problems can be specified and solved. The course primarily covers optimizations that are applicable to any target architecture; however, optimizations specific to parallel, distributed and storage-hierarchical systems also are discussed. Prerequisite: CSE 431S or CSE 425S.
Credit 3 units. EN: TU

E81 CSE 532S Advanced Multiparadigm Software Development
Intensive focus on advanced design and implementation of concurrent and distributed system software in C++. Topics covered include C++11 concurrency and synchronization features and software architecture patterns. Prerequisites: CSE 332S/CSE 504N or graduate standing and strong familiarity with C++; and CSE 422S or CSE 522S.
Credit 3 units. EN: TU

E81 CSE 535T Programming Language Theory
This course presents the theoretical foundations of programming languages, using formal techniques. We study how to define programming languages in a formal way, and how to prove meta-theoretic properties about them. Type theory, including powerful typing constructs like polymorphic and recursive types, receives particular attention. The work for the course includes theoretical exercises as well as a project, where students implement selected aspects of advanced programming languages. Prerequisites: CSE 240 and CSE 247.
Credit 3 units.

E81 CSE 536S Distributed System Design: Models and Languages
Modern computing environments are highly distributed. This has been the result of major advances in networking technology and their rapid assimilation by a society that functions in a highly distributed and decentralized manner. The goal of this course is to familiarize students with basic concepts, models and languages that shaped recent developments in distributed computing. The focus is on exploring new ways of thinking about computing and communication that made the development of distributed software systems possible. Competing concepts and design strategies will be examined both from a theoretical and a practical perspective. Prerequisites: CSE 240 and CSE 247.
Credit 3 units. EN: TU

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

E81 CSE 539S Concepts in Multicore Computing
Nowadays, the vast majority of computer systems are built using multicore processor chips. This fundamental shift in hardware design impacts all areas of computer science — one must write parallel programs in order to unlock the computational power provided by modern hardware.The goal of this course is to study concepts in multicore computing. We will examine the implications of the multicore hardware design, discuss challenges in writing high performance software, and study emerging technologies relevant to developing software for multicore systems. Topics include memory hierarchy, cache

coherence protocol, memory models, scheduling, high-level parallel language models, concurrent programming (synchronization and concurrent data structures), algorithms for debugging parallel software, and performance analysis. Prerequisites: CSE 332S and CSE 361S.
Credit 3 units. EN: TU

E81 CSE 541T Advanced Algorithms
Provides a broad coverage of fundamental algorithm design techniques with the focus on developing efficient algorithms for solving combinatorial and optimization problems. The topics covered include: greedy algorithms, dynamic programming, linear programming, NP-completeness, approximation algorithms, lower bound techniques, and on-line algorithms. Throughout this course there is an emphasis on correctness proofs and the ability to apply the techniques taught to design efficient algorithms for problems from a wide variety of application areas. Prerequisites: CSE 247 and 347.
Credit 3 units. EN: TU

E81 CSE 542T Advanced Data Structures and Algorithms
This course is concerned with the design and analysis of efficient algorithms, focusing principally on algorithms for combinatorial optimization problems. A key element in the course is the role of data structures in algorithm design and the use of amortized complexity analysis to determine how data structures affect performance. The course is organized around a set of core problems and algorithms, including the classical network optimization algorithms, as well as newer and more efficient algorithms. This core is supplemented by algorithms selected from the recent technical literature. Prerequisite: CSE 247.
Credit 3 units.

E81 CSE 543T Algorithms for Nonlinear Optimization
The course will provide an in-depth coverage of modern algorithms for the numerical solution of multidimensional optimization problems. Unconstrained optimization techniques including Gradient methods, Newton's methods, Quasi-Newton methods, and conjugate methods will be introduced. The emphasis is on constrained optimization techniques: Lagrange theory, Lagrangian methods, penalty methods, sequential quadratic programming, primal-dual methods, duality theory, nondifferentiable dual methods, and decomposition methods. The course will also discuss applications in engineering systems and use of state-of-the-art computer codes. Special topics may include large-scale systems, parallel optimization, and convex optimization. Prerequisites: Calculus I and Math 309.
Credit 3 units.

E81 CSE 544T Special Topics in Computer Science Theory
Cake-cutting algorithms consider the division of resources among a set of participants such that the recipients believe they have been treated fairly. In some cases, a given resource can be divided without loss of value, while in other cases, dividing a resource may lessen its value, perhaps significantly. Notions of fairness include proportionality, envy-freeness and equitability. This course is organized around a rich set of fair-division problems, studying the correctness, complexity, and applicability of algorithms for solving such problems. The problems and algorithms studied span millennia and include recent technical literature.
Credit 3 units.

E81 CSE 546T Computational Geometry
Computational geometry is the algorithmic study of problems that involve geometric shapes such as points, lines and polygons. Such problems appear in computer graphics, vision, robotics, animation, visualization, molecular biology, and geographic information systems. This course covers data structures that are unique to geometric computing, such as convex hull, Voronoi diagram, Delaunay triangulation, arrangement, range searching, KD-trees, and segment trees. Also covered are algorithms for polygon triangulation, shortest paths, the post office problem, and the art gallery problem. Prerequisite: CSE 247.
Credit 3 units.

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

E81 CSE 548T Concurrent Systems: Design and Verification
Formerly CSE 563T. Concurrency presents programmers with unprecedented complexity further exacerbated by our limited ability to reason about concurrent computations. Yet, concurrent algorithms are central to the development of software executing on modern multiprocessors or across computer networks. This course reviews several important classes of concurrent algorithms and presents a formal method for specifying, reasoning about, verifying, and deriving concurrent algorithms. The selected algorithms are judged to have made significant contributions to our understanding of concurrency. Rigorous treatment of the design and programming process is emphasized. Students entering this course must be familiar with predicate calculus and sequential algorithms. Upon completion of this course students will be able to reason completely formally about small concurrent programs and to apply systematically and correctly their formal skills to larger problems. Prerequisite: CSE 247.
Credit 3 units.

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

E81 CSE 552A Advanced Computer Graphics
This course covers advanced topics in graphics in the areas of modeling, rendering, volume rendering, image-based rendering and image processing. Topics include, but are not limited to, subdivision surfaces, splines, mesh simplification, implicit or blobby modeling, radiosity, procedural textures, filtering, BRDFs and procedural modeling. The class has several structured programming assignments and an optional final group project. Students are exposed to the wide variety of techniques

available in graphics and also pick one area to study in depth. Prerequisites: CSE 332S and CSE 452A.
Credit 3 units. EN: TU

E81 CSE 553S Advanced Mobile Robotics
This course covers advanced topics from the theory and practice of mobile robotics. Students read, present and discuss papers from the current research literature. There is a substantial programming project, in which students implement and test ideas from the current research literature on one of the department's research robot platforms. Prerequisites: CSE 550A and strong programming skills (preferably in C++).
Credit 3 units. EN: TU

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

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

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

E81 CSE 558A Motion Planning
This course studies the general motion planning problem: computing a sequence of motions that transforms a given (initial) arrangement of physical objects to another (goal) arrangement of those objects. Many motion planning methods were developed in the realm of robotics research. For example, a typical problem might be to find a sequence of motions (called a path) to move a robot from one position to another without colliding with any objects in its workspace. However, the general motion planning problem that will be studied arises in many other application domains as well. For example, assembly planning (e.g., finding a valid order for adding the parts when building an engine), mechanical CAD studies (e.g., can you remove a certain part from an engine without taking the engine apart), artificial life simulations (e.g., moving a herd of animals from one location to another), and medicine (e.g., can a drug molecule reach a protein molecule). Prerequisite: CSE 247.
Credit 3 units. EN: TU

E81 CSE 559A Computer Vision
Computer vision is the process of automatically extracting information from images and video. This course covers imaging geometry (camera calibration, stereo, and panoramic image stitching), and algorithms for video surveillance (motion detection and tracking), segmentation and object recognition. Final projects for the course will explore challenges in analysis of real-world data. Students with non-standard backgrounds (such as video art, or the use of imaging in physics and biology) are encouraged to contact the instructor. Prerequisites: CSE 247 and linear algebra.
Credit 3 units. EN: TU

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

E81 CSE 561M Computer Systems Architecture II
Advanced techniques in computer system design. Selected topics from: processor and system-on-chip design (multicore organization, system-level integration), run-time systems, memory systems (topics in locality and special-purpose memories), I/O subsystems and devices, systems security, and power considerations. Prerequisite: CSE 560M or permission of instructor.
Credit 3 units. EN: TU

E81 CSE 564M Advanced Digital Systems Engineering
This course focuses on advance sensor design. The class covers various basic analog and digital building blocks that are common in most sensor integrated circuits. The class extensively uses state-of-the-art CAD program Cadence to simulate and analyze various circuit blocks. The first half of the course focuses

on analyzing various operational amplifiers, analog filters, analog memory and analog to digital converters. The second half of the course focuses on understanding the basic building blocks of imaging sensors. The class has a final project consisting of designing a smart sensor using Cadence tools. Prerequisites: ESE 232 and CSE 362M.
Credit 3 units. EN: TU

E81 CSE 565M 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).
Credit 3 units. EN: TU

E81 CSE 566S High Performance Computer Systems
Many applications make substantial performance demands upon the computer systems upon which those applications are deployed. In this context, performance is frequently multidimensional, including resource efficiency, power, execution speed (which can be quantified via elapsed run time, data throughput, or latency), etc. Modern computing platforms exploit parallelism and architectural diversity (e.g., co-processors such as graphics engines and/or reconfigurable logic) to achieve the desired performance goals. This course addresses the practical aspects of achieving high performance on modern computing platforms. This includes questions ranging from how the computing platform is designed to how are applications and algorithms expressed to exploit the platform's properties. Particular attention is given to the role of application development tools. Prerequisite: Familiarity with software development in Linux preferred, graduate standing or permission of instructor.
Credit 3 units. EN: TU

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

E81 CSE 568M Imaging Sensors
This course will cover topics on digital imaging sensors including basic operations of silicon photodetectors; CCD and CMOS passive and active sensor operation; temporal and spatial noise in CMOS sensors; spatial resolution and MTF; SNR and dynamic range; high dynamic range architectures and application specific imaging sensors such as polarization imaging and fluorescent imaging sensors. Prerequisites: CSE 260M and ESE 232.
Credit 3 units.

E81 CSE 569M Parallel Architectures and Algorithms
A number of 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.
Credit 3 units. EN: TU

E81 CSE 570S Recent Advances in Networking
This course covers the latest advances in networking. The topics include Networking Trends, Data Center Network Topologies, Data Center Ethernet, Carrier IP, Multi-Protocol Label Switching (MPLS), Carrier Ethernet, Virtual Bridging, LAN Extension and Virtualization using Layer 3 Protocols, Virtual Routing Protocols, Internet of Things (IoT), Datalink Layer and Management Protocols for IoT, Networking Layer Protocols for IoT, 6LoWPAN, RPL, Messaging Protocols for IoT, MQTT, OpenFlow, Software Defined Networking (SDN) Network Function Virtualization (NFV), Big Data, Networking Issues for Big Data, Network Configuration, and Data Modeling, NETCONF, YIN, YANG, BEEP, and UML. Prerequisite: CSE 473S or equivalent.
Credit 3 units. EN: TU

E81 CSE 571S Network Security
A comprehensive treatment of network security. Topics include Security Overview, Classical Encryption Techniques, Block Ciphers and DES, Basic Concepts in Number Theory and Finite Fields, Advanced Encryption Standard (AES), Block Cipher Operations, Pseudo Random Number Generation and Stream Ciphers, Number Theory, Public Key Cryptography, other Public Key Cryptosystems, Cryptographic Hash Functions, Message Authentication Codes, Digital Signatures, Key Management and Distribution, User Authentication Protocols, Network Access Control and Cloud Security, Transport Level Security, Wireless Network Security, Electronic Mail Security, IP Security, Intrusion Detection, and Malicious Software. Prerequisite: CSE 473S.
Credit 3 units. EN: TU

E81 CSE 573S Protocols for Computer Networks
An introduction to the design, performance analysis and implementation of existing and emerging computer network protocols. Protocols include multiple access protocols (e.g., CSMA/CD, token ring), internet, working with the internet protocol (IP), transport protocols (e.g., UDP, TCP), high-speed bulk transfer protocols, and routing protocols (e.g., BGP, OSPF). General topics include error control, flow control, packet switching, mechanisms for reliable, ordered and bounded-time packet delivery, host-network interfacing and protocol implementation models. Substantial programming exercises supplement lecture topics. Prerequisite: CSE 473S or permission of the instructor.
Credit 3 units. EN: TU

E81 CSE 574S Wireless and Mobile Networking
First course in wireless networking providing a comprehensive treatment of wireless data and telecommunication networks. Topics include recent trends in wireless and mobile networking, wireless coding and modulation, wireless signal propagation, IEEE 802.11a/b/g/n/ac wireless local area networks, 60 GHz millimeter wave gigabit wireless networks, vehicular wireless networks, white spaces, IEEE 802.22 regional area networks, Bluetooth and Bluetooth Smart, wireless personal area networks, wireless protocols for Internet of Things, ZigBee, cellular networks: 1G/2G/3G, LTE, LTE-Advanced, and 5G. Prerequisites: CSE 473S or permission of the instructor.
Credit 3 units. EN: TU

E81 CSE 577M Design and Analysis of Switching Systems
Switching is a core technology in a wide variety of communication networks, including the internet, circuit-switched telephone networks and optical fiber transmission networks. The last decade has been a time of rapid development for switching technology in the internet. Backbone routers with 10 Gb/s links and aggregate capacities of hundreds of gigabits per second are becoming common, and advances in technology are now making multi-terabit routers practical. This course is concerned with the design of practical switching systems and evaluation of their performance and complexity. Prerequisites: CSE 247, 473S and ESE 326.
Credit 3 units. EN: TU

E81 CSE 581T Approximation Algorithms
Numerous optimization problems are intractable to solve optimally. The intractability of a problem could come from the problem's computational complexity, for instance the problem is NP-Hard, or other computational barriers. To cope with the inability to find an optimal algorithm, one may desire an algorithm that is guaranteed to return a solution that is comparable to the optimum. Such an algorithm is known as an approximation algorithm. Approximation algorithms are a robust way to cope with intractability, and they are widely used in practice or are used to guide the development of practical heuristics. The area of approximation algorithms has developed a vast theory, revealing the underlying structure of problems as well as their different levels of difficulty. The majority of this course will focus on fundamental results and widely applicable algorithmic and analysis techniques for approximation algorithms. Prerequisite: CSE 347.
Credit 3 units. EN: TU

E81 CSE 582T Complexity Theory
An introduction to the quantitative theory of computation with limited resources. The course examines the relative power of limited amounts of basic computational resources, such as time, memory, circuit size and random bits, as well as parallel, nondeterministic, alternating and interactive machine models. Models that capture special kinds of computational problems, such as counting problems or approximate solutions, will also be introduced and related to the standard models. This examination will emphasize surprising relationships between seemingly disparate resources and kinds of computational problems. The course will also discuss some meta-theory, illuminating the weaknesses of standard mathematical techniques of the field against its notorious open conjectures. Prerequisites: CSE 347 and mathematical maturity. CSE 547T recommended.
Credit 3 units. EN: TU

E81 CSE 583A Topics in Computational Molecular Biology
Formerly CSE 543T. In-depth discussion of problems and methods in Computational Molecular biology. Each year three topics are covered and those change yearly. Prerequisite: Biol 5495 or instructor's consent.
Same as L41 Biol 5497
Credit 2 units.

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

E81 CSE 587A Algorithms for Computational Biology
This course is a survey of algorithms and mathematical methods in biological sequence analysis (with a strong emphasis on probabilistic methods) and systems biology. Sequence analysis topics include introduction to probability, probabilistic inference in missing data problems, hidden Markov models (HMMs), profile HMMs, sequence alignment, and identification of transcription-factor binding sites. Systems biology topics include discovery of gene regulatory networks, quantitative modeling of gene regulatory networks, synthetic biology, and (in some years) quantitative modeling of metabolism. Prerequisites: CSE 131 or CSE 501N.
Credit 3 units.

E81 CSE 5ELE CSE Elective (Grad)
Credit variable, maximum 9 units.

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

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

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

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

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

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

E81 CSE 7600 Research Seminar on Computer Engineering
Research seminars examine publications, techniques, approaches and strategies within an area of computer science and engineering. Seminars are highly participational: Students are expected to take turns presenting material, to prepare for seminar by reading any required material, and to contribute to the group's discussions. The actual topics covered in a seminar will vary by semester and instructor. Interested students are encouraged to obtain a syllabus from the instructor's webpage or by contacting the instructor.
Credit 1 unit.

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

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

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

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

E81 CSE 883 Master's Continuing Student Status

E81 CSE 885 Master's Nonresident

E81 CSE 886 Doctoral Nonresident

Electrical & Systems Engineering

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

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

- Applied mathematics, systems & control
- Electronics & optics
- Signal processing, imaging & communications

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

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

Phone:	314-935-5565
Website:	http://ese.wustl.edu

Faculty

Chair

Arye Nehorai (https://engineering.wustl.edu/Profiles/Pages/Arye-Nehorai.aspx)
Eugene and Martha Lohman Professor of Electrical Engineering
PhD, Stanford University
Signal processing, imaging, biomedicine, communications

Associate Chair

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

Endowed Professors

R. Martin Arthur (https://engineering.wustl.edu/Profiles/Pages/Martin-Arthur.aspx)
Newton R. and Sarah Louisa Glasgow Wilson Professor of Engineering
PhD, University of Pennsylvania
Ultrasonic imaging, electrocardiography

Joseph A. O'Sullivan (https://engineering.wustl.edu/Profiles/Pages/Joseph-OSullivan.aspx)
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 (https://engineering.wustl.edu/Profiles/Pages/Lan-Yang.aspx)
Edward H. & Florence G. Skinner Professor of Engineering
PhD, California Institute of Technology
Nano/micro photonics, ultra high-quality optical microcavities, ultra-low-threshold microlasers, nano/micro fabrication, optical sensing, single nanoparticle detection, photonic molecules, photonic materials

Professor

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

Humberto Gonzalez (https://engineering.wustl.edu/Profiles/Pages/Humberto-Gonzalez.aspx)
PhD, University of California, Berkeley
Cyber-physical systems, hybrid dynamical systems, optimization, robotics

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

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

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

Donald L. Snyder
PhD, Massachusetts Institute of Technology
Communication theory, random process theory, signal processing, biomedical engineering, image processing, radar

Barry E. Spielman
PhD, Syracuse University
High-frequency/high-speed devices, RF & MW integrated circuits, computational electromagnetics

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

Professor of Practice

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

Dennis Mell
MS, University of Missouri-Rolla

Ed Richter
BSEE, Virginia Tech

Senior Lecturer

Martha Hasting
PhD, Saint Louis University

Lecturers

Randall Brown
PhD, Washington University

Randall Hoven
MS, Washington University
MSEE, Johns Hopkins University
Sensor/data fusion, Kalman filters, navigation, target tracking

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

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

Jason Trobaugh
DSc, Washington University

Jinsong Zhang
PhD, University of Miami
Wireless communication systems, wireless sensor networks, target tracking/data fusion, machine learning/pattern classification

Research Professor

Julius Goldstein
PhD, University of Rochester
Auditory system, hearing perception, modeling auditory perception.

Research Associate Professor

David Corman
PhD, University of Maryland
Cyber Physical Systems (CPS), security for CPS, unmanned systems, manufacturing

Research Assistant Professor

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

Professors Emeriti

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

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

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

Marvin J. Fisher
PhD, University of Illinois
Energy conversion, power electronics

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

Degree Requirements

Please refer to the following sections for information about:

- Doctoral Degrees (p. 37)
- MS in Electrical Engineering (p. 38)
- MS in Systems Science & Mathematics (p. 38)
- MS in Data Analytics and Statistics (p. 39)
- Master of Control Engineering (p. 39)
- Master of Engineering in Robotics (p. 39)
- Imaging Science & Engineering (p. 40)

Doctoral Degrees

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

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

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

The doctoral degree should ordinarily take no more than five years to complete, for students who enter the program with a baccalaureate degree. While individual circumstances will vary, the typical timeline will be as follows:

- Year 1: Course work and written qualifying examination
- Year 2: Course work, preliminary research, research advisory committee selection
- Year 3: Course work and preliminary research examination
- Year 4: Research
- Year 5: Research, completion of dissertation, and final oral examination

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

Master's Degrees

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

Course Option

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

Thesis Option

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

MS in Electrical Engineering

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

- A minimum of 15 of these credit hours must be at the graduate level in electrical engineering subjects taught by the Department of Electrical & Systems Engineering (ESE). The list of courses that may be used to satisfy the 15-credit graduate-level course requirement is:
  - ESE 513 Convex Optimization and Duality Theory
  - ESE 415 Optimization
  - ESE 516 Optimization in Function Space
  - ESE 520-529 Applied probability category
  - ESE 530-539 Applied physics and electronics category
  - ESE 540-549 Control category
  - ESE 550-559 Systems category
  - ESE 560-569 Computer engineering category
  - ESE 570-579 Communications category
  - ESE 580-589 Signal and image processing category
  - ESE 599 Master's Research (thesis option only, max 6 units)
- The remaining courses in the program may be selected from senior- or graduate-level courses in ESE or elsewhere in the university. Courses outside of ESE must be in technical subjects relevant to electrical engineering and require the department's approval. Only one CSE graduate course which does not carry CSE graduate credit may be used to satisfy the MSEE degree.
- A maximum of one 500-level cross-listed ESE course, whose home department is outside of ESE, may be applied toward the 15-credit graduate-level requirement.
- At least 15 units of the 30 total units applied toward the MSEE degree must be in ESE courses which, if cross-listed, have ESE as the home department.
- A maximum of 6 credits may be transferred from another institution and applied toward the MSEE degree. Regardless of subject or level, all transfer courses are treated as electives and do not count toward the requirement of 15 credit hours of graduate-level electrical engineering courses.
- ESE 590 Electrical and Systems Engineering Graduate Seminar must be taken each semester. Master of Science students must attend at least three seminars per semester.
- The degree program must be consistent with the residency and other applicable requirements of Washington University and the School of Engineering & Applied Science.
- Students must have a cumulative grade point average of at least 3.2 out of a possible 4.0 over all courses applied toward the degree.

MS in Systems Science & Mathematics

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

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

ESE 551	Linear Dynamic Systems I	3
ESE 553	Nonlinear Dynamic Systems	3
ESE 520	Probability and Stochastic Processes	3
ESE 415	Optimization [1]	3
and one chosen from the following courses:		
ESE 524	Detection and Estimation Theory	3
or ESE 544	Optimization and Optimal Control	
or ESE 545	Stochastic Control	
or ESE 557	Hybrid Dynamic Systems	
Total units		15

[1] ESE 516 may be substituted for ESE 415.

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

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

MS in Data Analytics and Statistics

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

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

ESE 520	Probability and Stochastic Processes	3
or Math 493	Probability	
ESE 524	Detection and Estimation Theory	3
Math 494	Mathematical Statistics	3
CSE 514A	Data Mining	3
or CSE 517A	Machine Learning	
or CSE 530S	Database Management Systems	
ESE 415	Optimization	3
or ESE 516	Optimization in Function Space	
or ESE 518	Optimization Methods in Control	
Total units		15

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

Master of Control Engineering

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

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

ESE 441	Control Systems	3
ESE 543	Control Systems Design by State Space Methods	3
ESE 520	Probability and Stochastic Processes	3
and at least two of the following six courses:		
ESE 415	Optimization	3
or ESE 425	Random Processes and Kalman Filtering	
or ESE 551	Linear Dynamic Systems I	
or ESE 552	Linear Dynamic Systems II	
or ESE 553	Nonlinear Dynamic Systems	
or ESE 547	Robust and Adaptive Control	

- Elective Courses (15 units): The 15 units of electives should be courses of a technical nature at the senior and graduate levels approved by the Program Director.
- 6 units may be transferred from another school as electives provided that the courses were not needed for the student's bachelor's degree.
- ESE 590 Electrical and Systems Engineering Graduate Seminar must be taken each semester.
- The degree program must be consistent with the residency and other applicable requirements of Washington University and the School of Engineering & Applied Science.
- Students must have a cumulative grade point average of at least 3.2 out of a possible 4.0 over all courses applied toward the degree.

Master of Engineering in Robotics

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

- The degree requires 30 units. The courses must be 400-level or higher and they must include at least 15 units of 500-level courses.
- Students must have a cumulative grade point average of at least 3.2 out of a possible 4.0 over all courses applied toward the degree.
- Required courses (12 units) for the MEng in Robotics degree include:

ESE 446	Robotics: Dynamics and Control (Spring)	3
ESE 447	Robotics Laboratory (Fall, Spring)	3
ESE 551	Linear Dynamic Systems I (Fall)	3
CSE 511A	Introduction to Artificial Intelligence	3
or CSE 517A	Machine Learning	

ESE 590	Electrical and Systems Engineering Graduate Seminar (must be taken each semester)	0
Total units		12

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

Optimization and Simulation Group

ESE 403	Operations Research (Fall)	3
ESE 407	Analysis and Simulation of Discrete Event Systems (Spring)	3
ESE 415	Optimization (Spring)	3

Control Engineering Group

ESE 441	Control Systems (Fall)	3
or		
MEMS 4301	Modeling, Simulation and Control (Spring)	
ESE 444	Sensors and Actuators (Fall)	3
ESE 425	Random Processes and Kalman Filtering (Fall)	3
ESE 543	Control Systems Design by State Space Methods (Fall)	3
ESE 552	Linear Dynamic Systems II (Spring)	3
ESE 553	Nonlinear Dynamic Systems (Spring)	3

Computer Science Group

CSE 511A	Introduction to Artificial Intelligence	3
CSE 517A	Machine Learning	3
CSE 520S	Real-Time Systems (Fall)	3
CSE 521S	Wireless Sensor Networks	3
CSE 546T	Computational Geometry	3
CSE 553S	Advanced Mobile Robotics (Spring)	3
CSE 556A	Human-Computer Interaction Methods (Fall)	3
CSE 568M	Imaging Sensors (Spring)	3
CSE 559A	Computer Vision (Spring)	3

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

ESE 500	Independent Study (Fall, Spring and Summer)	var.
CSE 500	Independent Study (Fall, Spring and Summer)	var.
MEMS 500	Independent Study (Fall, Spring and Summer)	var.

Preparation for the MEng in Robotics Program

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

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

Graduate Certificate in Imaging Science & Engineering

A certificate program in Imaging Science & Engineering (IS&E) is offered jointly by the departments of Electrical & Systems Engineering, Computer Science & Engineering, and Biomedical Engineering. Built on the strengths in imaging science throughout the university, this multidisciplinary program is constructed to expose students to the breadth of imaging research activities at Washington University. The requirements of the program vary by department, but are flexible in allowing students and their advisers to construct academic programs ideally suited to complement their individual research programs. Students in the program are brought together for a joint seminar course, and all students engage in a practicum in imaging science and engineering. For more information, please refer to either the Department of Electrical & Systems Engineering website (http://ese.wustl.edu/graduateprograms/Pages/ImagingScienceAndEngineering.aspx) or contact the department directly.

Entering & Completing the Program

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

Upon the awarding of a graduate degree by their home department and by completing certain requirements of the program, students are awarded a certificate indicating their successful participation in the IS&E program. The requirements for receiving a certificate are: acceptance into the IS&E program, completion of core subjects as specified by the student's home department, completion of requirements for a graduate degree in the student's home department, participation in the tutorial seminar required for all students in the IS&E program, and completion of the practicum required of all students in the IS&E program.

Courses of Instruction

Fundamentals underlying imaging science and engineering and the application of these fundamentals to contemporary problems of importance form the theme of the program of instruction in the IS&E program. Topics that can be studied include:

- physics of sources detectors and devices that yield image data
- instrumentation used to acquire image data
- mathematical models and methods for representing and understanding image data and images produced from such data
- conventional and model-based image processing, restoration and reconstruction
- image-based decision, estimation, cognition and control
- computer architectures, parallel computers, and specialized digital systems for processing and simulating image data
- physics, psychophysics, and technology of image display
- image digitization, compression, storage and transmission
- image representation, interpretation and evaluation

The IS&E program is structured around required and elective courses that are offered in the participating departments. Each participating department specifies required core courses for their students in the program. All students in the program take a tutorial seminar in imaging during their first year, and all participate in a practicum in which they are exposed to research having a strong imaging component.

Courses

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

E35 ESE 500 Independent Study
Opportunities for graduate students to explore possible areas of interest with individual faculty members. Coordinated study programs dealing with areas not covered by formal course work are possible. Independent study credit can be changed to research credit (ESE 599) any time during the semester if enrollment is appropriate. A final report must be submitted to the department.
Credit variable, maximum 3 units.

E35 ESE 501 Mathematics of Modern Engineering I
Vectors and vector spaces, matrix operations, system of linear equations, eigenvalues and eigenvectors, vector fields, line and surface integrals, solutions to ordinary and partial differential equations, series expansions, Fourier series. Prerequisites: ESE 318 and 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 502 Mathematics of Modern Engineering II
Techniques of solving ordinary differential equations with constant coefficients, Laplace's Transform, solutions for the heat and wave equations, Laplace's Equation, Legendre and Bessel Function, Introduction to function of a complex variable, conformal mapping, contour integrals. 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 503 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 covered include linear and integer programming, network problems and dynamic programming. Prerequisites: Math 217 and familiarity with matrix or linear algebra, or permission of instructor.
Credit 3 units.

E35 ESE 512 Advanced Numerical Analysis
Special topics chosen from numerical solution of partial differential equations, uniform and least-squares approximation spline approximation, Galerkin methods and finite element approximation, functional analysis applied to numerical mathematics, and other topics of interest. Prerequisite: ESE 511 or consent of instructor.
Credit 3 units. 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 4111.
Credit 3 units.

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

E35 ESE 516 Optimization in Function Space
Linear vector spaces, normed linear spaces, Lebesque integrals, the Lp spaces, linear operators, dual space, Hilbert spaces. Projection theorem, Hahn-Banach theorem. Hyperplanes and convex sets, Gateaux and Frächet differentials, unconstrained minima, adjoint operators, inverse function theorem. Constrained minima, equality constraints, Lagrange multipliers, calculus of variations, Euler-Lagrange equations, positive cones, inequality constraints. Kuhn-Tucker theorem, optimal control theory,

Pontryagin's maximum principle, successive approximation methods, Newton's methods, steepest descent methods, primal-dual methods, penalty function methods, multiplier methods. Prerequisite: Math 4111.
Credit 3 units.

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 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
Study of detection, estimation and modulation theory; detection of signals in noise; estimation of signal parameters; linear estimation theory. Kalman-Bucy and Wiener filters, nonlinear modulation theory, optimum angle modulation. Prerequisite: ESE 520.
Credit 3 units. EN: TU

E35 ESE 525 Random Processes and Kalman Filtering
Review of probability and random variables; random processes; linear dynamic system response to stochastic inputs; mean square estimation; discrete and continuous Kalman filters; extended Kalman filter for nonlinear systems; maximum likelihood; Wiener filtering and special factorization, LQG/LTR control; topics in system identification; particle filters. Control, estimation (Kalman filter), and system identification problems using MATLAB. Prerequisite: ESE 326 or equivalent.
Credit 3 units.

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 theory, design, fabrication and application of photonic materials and micro/nano photonic devices. Interaction of light and matter, propagation of light in waveguide, nonlinear optical effect and optical properties of nano/micro structure, the device principles of silicon-based waveguide, filter, photodetector, modulator and laser devices. Prerequisite: ESE 330.
Credit 3 units. EN: TU

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

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

E35 ESE 536 Introduction to Quantum Optics
This course covers the following topics: quantum mechanics for quantum optics, radiative transitions in atoms, lasers, photon statistics (photon counting, Sub-/Super-Poissionian 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 537 Advanced Electromagnetic Theory
Solution of electromagnetic boundary value problems, applications to engineering analysis and design. First semester: mathematical methods for electrostatics, magnetostatics and electrodynamics, emphasizing Green's function techniques. Second semester: radiation and diffraction; waveguides, antennas and optics. Vector boundary conditions, Green's dyadics, variational techniques. Prerequisite: advanced calculus, ESE 430 or equivalent.
Credit 3 units. EN: TU

E35 ESE 538 Advanced Electromagnetic Engineering
This course begins with a brief review of prerequisite topics. The following topics are treated for guided-wave systems: solution for and use of mode sets in planar and cylindrical guided-wave systems; use of alternative mode sets for inhomogeneous guided-wave systems; dielectric-based and surface-guided wave systems. Methods for launching waves in systems are studied, including: modal expansions, current-based launchers using electric or magnetic coupling techniques, and aperture excitation. Perturbational and variational methods are studied for representing important characteristics of guided-wave and resonator systems. Modal expansions are related to a one- and two-port microwave network treatment of obstacles and circuit elements and junctions in guide-wave systems. The course then shifts to the study of modern numerical methods for developing frequency- and time-domain solutions for guided-wave and two-dimensional radiation and scattering problems encountered in electromagnetic engineering applications. The methods learned are applied to a project selected and carried out by each student. Prerequisites: equivalent of ESE 330, ESE 430, and ESE 537 or instructor permission.
Credit 3 units.

E35 ESE 539 Advanced Electromagnetics: Radiation and Scattering
This course starts with a brief review of fundamental concepts including: wave behavior, the generalized source concept, basics of radiation, duality, uniqueness, image theory, the equivalence principle and reciprocity. The focus then turns to important definitions of antenna parameters and qualities. Important antenna types are addressed, including resonant and traveling-wave types. Linear and two-dimensional arrays are treated. Phased-array and active-aperture systems are described. Finally, smart antenna concepts are presented. Prerequisite: ESE 330 or equivalent.
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
Introduction to the theory of stochastic differential equations based on Wiener processes and Poisson counters, and an introduction to random fields. The formulation and solution of problems in nonlinear estimation theory. The Kalman-Bucy filter and nonlinear analogues. Identification theory. Adaptive systems. Applications. Prerequisites: ESE 520 and ESE 551.
Credit 3 units. EN: TU

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

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

E35 ESE 549 Special Topics in Control
Credit 3 units.

E35 ESE 551 Linear Dynamic Systems I
Input-output and state-space description of linear dynamic systems. Solution of the state equations and the transition matrix. Controllability, observability, realizations, pole-assignment, observers and decoupling of linear dynamic systems. Prerequisite: ESE 351.
Credit 3 units. EN: TU

E35 ESE 552 Linear Dynamic Systems II
Least squares optimization problems. Riccati equation, terminal regulator and steady-state regulator. Introduction to filtering and stochastic control. Advanced theory of linear dynamic systems. Geometric approach to the structural synthesis of linear multivariable control systems. Disturbance decoupling, system invertibility and decoupling, extended decoupling and the internal model principle. Prerequisite: ESE 551.
Credit 3 units. EN: TU

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

E35 ESE 554 Advanced Nonlinear Dynamic Systems
Controllability, observability of nonlinear systems, examined from the viewpoint of differential geometry. Differentiable manifolds, vector fields, distributions on a manifold, Frobenius' theorem, Lie algebras. Volterra series expansions of the input-output map. Transformation to normal forms. Exact linearization via feedback. Zero dynamics and related properties. Noninteracting control and disturbance decoupling. Controlled invariant distributions. Noninteracting control with internal stability. Prerequisite: ESE 553.
Credit 3 units.

E35 ESE 557 Hybrid Dynamic Systems
Theory and analysis of hybrid dynamic systems, which is the class of systems whose state is composed by continuous-valued and discrete-valued variables. Discrete-event systems models and language descriptions. Models for hybrid systems. Conditions for existence and uniqueness. Stability and verification of hybrid systems. Optimal control of hybrid systems. Applications to cyber-physical systems and robotics. Prerequisite: ESE 551.
Credit 3 units. 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, bus organization, RISC (Reduced Instruction Set Computers), and CISC (Complex Instruction Set Computers). 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 564 Advanced Digital Systems Engineering
This course focuses on advance sensor design. The class covers various basic analog and digital building blocks that are common in most sensor integrated circuits. The class extensively uses state-of-the-art CAD program Cadence to simulate and analyze various circuit blocks. The first half of the course focuses on analyzing various operational amplifiers, analog filters, analog memory and analog to digital converters. The second half of the course focuses on understanding the basic building blocks of imaging sensors. The class has a final project composed of designing a smart sensor using Cadence tools. Prerequisites: ESE 232 and CSE 362M.
Same as E81 CSE 564M
Credit 3 units. EN: TU

E35 ESE 565 Acceleration of Algorithms in Reconfigurable Logic
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 260.
Credit 3 units. EN: TU

E35 ESE 567 Computer Systems Analysis
Comparing systems using measurement, simulation and queueing models. Common mistakes and how to avoid them, selection of techniques and metrics, art of data presentation, summarizing measured data, comparing systems using sample

data, introduction to experimental design, fractional factorial designs, introduction to simulation, common mistakes in simulations, analysis of simulation results, random number generation, random variate generation, commonly used distributions, introduction to queueing theory, single queues, and queueing networks. The techniques of the course can be used to analyze and compare any type of systems including algorithms, protocols, network or database systems. Students do a project involving application of these techniques to a problem of their interest. 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 574 Digital Communications
Representation of signals by orthonormal expansion, spectral characteristic of digitally modulated signals, channel models, source models, results from information theory, efficient signaling with coded waveforms, intersymbol interference, equalization, optimum demodulation, decoding (including Viterbi decoder), probability of error, carrier and symbol synchronization, spread-spectrum methods. Corequisite: ESE 520.
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 577 Design and Analysis of Switching Systems
Switching is a core technology in a wide variety of communication networks, including the internet, circuit-switched telephone networks and optical fiber transmission networks. The last decade has been a time of rapid development for switching technology in the internet. Backbone routers with 10 Gb/s links and aggregate capacities of hundreds of gigabits per second are becoming common, and advances in technology are now making multi-terabit routers practical. This course is concerned with the design of practical switching systems and evaluation of their performance and complexity. Prerequisites: CSE 247, 473S and ESE 326.
Same as E81 CSE 577M
Credit 3 units. EN: TU

E35 ESE 581 Radar Systems
An introduction to the selection and processing of radar signals. Signal design for improving range and Doppler resolution, ambiguity functions, chirp and stepped-frequency waveforms, pulse-compression codes. Statistical models for radar data: range-spread, Doppler-spread, doubly spread reflectors. Matched-filter and estimator-correlator receivers for range and Doppler estimation. Tracking. Multiantenna radar receivers: interference rejection, adaptive canceling. Delay-Doppler radar-imaging using synthetic-aperture processing. Prerequisite: ESE 524.
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 585 Optical Imaging
A modern introduction to optical imaging. Topics include: propagation of waves, diffraction, scattering theory, multiple scattering and radiative transport, diffuse light, inverse scattering and other inverse problems, near-field optics. Applications to biomedical problems are discussed. Prerequisites: ESE 330 and ESE 351.
Credit 3 units. EN: TU

E35 ESE 586 Tomographic Systems
The study of systems for imaging the interior of an object from external measurements. Mathematical preliminaries: multidimensional linear systems, the Poisson process, maximum-likelihood estimation. Transmission, emission, reflection and magnetic resonance tomography. Line integral, strip integral, weighted integral, and divergent ray descriptions of tomographic data. The Radon transform. Reconstruction from ideal data: filtered back project, back-project filter, Fourier and inverse Radon-transform methods. Reconstruction from blurred and noisy data: confidence-weighting, minimum-divergence deblurring, and estimation-based methods. Techniques for treatment of mission data, attenuation and accidentals. Application to positron-emission, single-photon emission, X-ray and magnetic-resonance tomography and to high-resolution radar-imaging. Computer architectures for producing tomographic imagery. Prerequisite: ESE 520.
Credit 3 units. EN: TU

E35 ESE 587 Ultrasonic Imaging
Propagation of ultrasound in homogeneous media, near-field and far-field descriptions, refraction and diffraction, dispersive media models, acoustic wave equation formulations and solutions. Basic elements of transducer, pulser and receiver design. The use of linear versus logarithmic amplifiers. Time-gain compensation, scan conversion and image generation in single-transducer systems. Phased-array imaging systems. Synthetic-aperture acquisition, synthetic-focus image generation. Ellipsoidal back projection using the complete dataset. Design of restoration filters to compensate for diffraction effects of the transducer. Estimation of media properties from images. Prerequisite: ESE 351.
Credit 3 units. EN: TU

E35 ESE 588 Quantitative Image Processing
Introduction to the modeling processing and display of images. Two-dimensional linear systems and linear processing of images. Two-dimensional transform methods. Image acquisition and display technology. Psychophysical aspects of vision. Case studies in image processing (examples: tomography, radiology, ultrasonic imaging). Special algorithms for image processing (examples: boundary detection, segmentation, compression, interactive processing and display). Prerequisites: ESE 326, ESE 482.
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 and Systems Engineering Graduate Seminar
This pass/fail course is required for the MSc, 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. MSc 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 597 Practicum in Imaging Science and Engineering
This course provides students in the Imaging Science and Engineering program with opportunities to participate, early in their graduate studies, in projects involving image data. A list of IS&E faculty having potential projects of interest is provided.

It is the student's responsibility to interview with such faculty in order to identify a project for themselves to be completed in one semester. A written report documenting the project goals, relevant literature and results obtained is required at the end of the project. To receive credit for completing the practicum, the report must be accepted by the supervisor of the project and a committee of IS&E faculty. This course is graded pass/fail. Prerequisite: admission to Imaging Science and Engineering program.
Credit 1 unit. EN: TU

E35 ESE 599 Master's Research
Credit variable, maximum 3 units.

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

E35 ESE 883 Master's Continuing Student Status

E35 ESE 884 Doctoral Continuing Student Status

E35 ESE 885 Master's Nonresident

E35 ESE 886 Doctoral Nonresident

Energy, Environmental & Chemical Engineering

The Department of Energy, Environmental & Chemical Engineering (EECE) provides integrated and multidisciplinary programs of scientific education in cutting-edge areas, including the **PhD in Energy, Environmental & Chemical Engineering**. Research and educational activities of the department are organized into four clusters: aerosol science & engineering; engineered aquatic processes; multiscale engineering; metabolic engineering & systems biology. These overlapping clusters address education and research in four thematic areas: energy; environmental engineering science; advanced materials; and sustainable technology for public health and international development. In addition to the core faculty in the department, faculty in the schools of Medicine, Arts & Sciences, Business, Law, and Social Work collaborate to provide students with a holistic education and to address topical problems of interest.

Two master's programs are offered through the department: **Master of Engineering in Energy, Environmental & Chemical Engineering (MEng)** and **Master of Engineering in Energy, Environmental & Chemical Engineering/Master of Business Administration (MEng/MBA)**. The MEng degree provides students with critical scientific and engineering skill sets; leadership training for management, economics, and policy decision; and the opportunity to specialize in one of five pathways. The MEng/MBA is a dual degree between the School of Engineering & Applied Science and the Olin Business School which provides engineering and business approaches to issues of sustainability, energy, the environment, and corporate social responsibility. Interested students must apply and be accepted to both programs before admission is provided to the MEng/MBA dual degree program.

The department is a key participant in the university's Energy, Environment & Sustainability (http://sustainability.wustl.edu) initiative and supports both the International Center for Advanced Renewable Energy and Sustainability (I-CARES (http://icares.wustl.edu)) and the McDonnell Academy Global Energy and Environment Partnership (MAGEEP (http://mageep.wustl.edu)). Major externally funded research centers in the department include the Consortium for Clean Coal Utilization (http://cleancoal.wustl.edu), the National Nanotechnology Infrastructure Node (http://nano.wustl.edu), and the Solar Energy Research Institute for India and the United States (SERIIUS (http://www.seriius.org)).

Phone:	314-935-5548
Website:	http://eece.wustl.edu

Faculty

Chair and Endowed Professor

Pratim Biswas (https://engineering.wustl.edu/Profiles/Pages/Pratim-Biswas.aspx)
Lucy and Stanley Lopata Professor
PhD, California Institute of Technology
Aerosol science and engineering, air quality and pollution control, nanotechnology, environmentally benign energy production

Endowed Professors

Richard L. Axelbaum (https://engineering.wustl.edu/Profiles/Pages/Richard-Axelbaum.aspx)
Stifel and Quinette Jens Professor
PhD, University of California, Davis
Combustion, advanced energy systems, clean coal, aerosols, nanoparticle synthesis, rechargeable battery materials, thermal science

Milorad P. Dudukovic (https://engineering.wustl.edu/Profiles/Pages/Milorad-Dudukovic.aspx)
Laura and William Jens Professor
PhD, Illinois Institute of Technology
Chemical reaction engineering, multiphase reactors, visualization of multiphase flows, tracer methods, environmentally benign processing

Daniel E. Giammar (https://engineering.wustl.edu/Profiles/Pages/Daniel-Giammar.aspx)
Walter E. Browne Professor of Environmental Engineering
PhD, California Institute of Technology
Aquatic chemistry, environmental engineering, water quality, water treatment

Professor

Palghat A. Ramachandran (https://engineering.wustl.edu/Profiles/Pages/Palghat-Ramachandran.aspx)
PhD, University of Bombay
Chemical reaction engineering, applied mathematics, process modeling, waste minimization, environmentally benign processing

Associate Professors

John Fortner (https://engineering.wustl.edu/Profiles/Pages/John-Fortner.aspx)
I-CARES Career Development Assistant Professor
PhD, Rice University
Environmental engineering, aquatic processes, water treatment, remediation, and environmental implications and applications of nanomaterials

John T. Gleaves (https://engineering.wustl.edu/Profiles/Pages/John-Gleaves.aspx)
PhD, University of Illinois
Heterogeneous catalysis, particle chemistry

Young-Shin Jun (https://engineering.wustl.edu/Profiles/Pages/Young-Shin-Jun.aspx)
Harold D. Jolley Career Development Associate Professor
PhD, Harvard University
Aquatic processes, molecular issues in chemical kinetics, environmental chemistry, surface/physical chemistry, environmental engineering, biogeochemistry, nanotechnology

Yinjie Tang (https://engineering.wustl.edu/Profiles/Pages/Yinjie-Tang.aspx)
Francis Ahmann Career Development Associate Professor
PhD, University of Washington, Seattle
Metabolic engineering, bioremediation

Jay R. Turner (https://engineering.wustl.edu/Profiles/Pages/Jay-Turner.aspx)
DSc, Washington University
Air quality planning and management; aerosol science and engineering, green engineering

Brent Williams (https://engineering.wustl.edu/Profiles/Pages/Brent-Williams.aspx)
Raymond R. Tucker Distinguished I-CARES Career Development Assistant Professor
PhD, University of California, Berkeley
Aerosols, global climate issues, atmospheric sciences

Assistant Professors

Rajan Chakrabarty (https://engineering.wustl.edu/Profiles/Pages/Rajan-Chakrabarty.aspx)
PhD, University of Nevada, Reno
Characterizing the radiative properties of carbonaceous aerosols in the atmosphere; and researching gas phase aggregation of aerosols in cluster-dense conditions

Marcus Foston (https://engineering.wustl.edu/Profiles/Pages/Marcus-Foston.aspx)
PhD, Georgia Institute of Technology
Utilization of biomass resources for fuel and chemical production, renewable synthetic polymers

Cynthia Lo (https://engineering.wustl.edu/Profiles/Pages/Cynthia-Lo.aspx)
PhD, Massachusetts Institute of Technology
Solar energy conversion, materials, environmental interfaces, catalysis, computational chemistry and molecular modeling

Tae Seok Moon (https://engineering.wustl.edu/Profiles/Pages/Tae-Seok-Moon.aspx)
PhD, Massachusetts Institute of Technology
Metabolic engineering and synthetic biology

Elijah Thimsen (https://engineering.wustl.edu/Profiles/Pages/Elijah-Thimsen.aspx)
PhD, Washington University
Gas-phase synthesis of inorganic nanomaterials for energy applications, and novel plasma synthesis approaches

Fuzhong Zhang (https://engineering.wustl.edu/Profiles/Pages/Fuzhong-Zhang.aspx)
PhD, University of Toronto
Metabolic engineering, protein engineering, synthetic and chemical biology

Research Associate Professor

Tianxiang Li
PhD, University of Kentucky
Combustion and applications in energy, pollutant control, biofuel synthesis, flame synthesis of nano-materials

Research Assistant Professors

Su Huang
PhD, University of Washington, Seattle
Photovoltaic materials and devices, nonlinear optical materials for photonic devices

Benjamin Kumfer
DSc, Washington University
Advanced coal technologies, biomass combustion, aerosol processes and health effects of combustion-generated particles

Lecturer

Janie Brennan
PhD, Purdue University
Biomaterials, synthetic biology, engineering education

Joint Faculty

Steven George (https://engineering.wustl.edu/Profiles/Pages/Steven-George.aspx)
Elvera and William Stuckenberg Professor
Chair, Department of Biomedical Engineering
PhD, University of Washington, Seattle
Tissue engineering; microphysiological systems; vascularizing engineered tissues

Himadri Pakrasi
PhD, University of Missouri-Columbia
Systems biology, photosynthesis, metal homeostasis

Nathan Ravi (http://ophthalmology.wustl.edu/Faculty/Ravi_N.aspx)
PhD, Virginia Polytechnic Institute
Cataract, ocular biomaterials

Adjunct Faculty

Robert Heider
MME, Washington University
Process control and process design

Timothy Michels
MA, Washington University
Energy economics, building construction and equipment sciences

Nicholas J. Nissing
BS, Washington University
Product development and process design

Research Associate

Raymond Ehrhard
BS, University of Missouri-Rolla
Water and wastewater treatment technologies, process energy management

Professor of Practice

James Harlan
PhD, Harvard University, Kennedy School of Government
Technology development economics and venture finance

Senior Professor

Rudolf B. Husar
PhD, University of Minnesota
Environmental informatics, aerosol science and engineering

Degree Requirements

Please refer to the following sections for information about the:

- Doctor of Philosophy (p. 49)
- Master of Engineering (p. 49)
- Combined MEng/MBA (p. 50)

Doctor of Philosophy (PhD) in Energy, Environmental & Chemical Engineering (EECE)

The doctoral degree requires a total of 72 credits beyond the bachelor's degree. Of these, a minimum of 36 must be graduate course work and a minimum of 30 must be doctoral thesis research units. To be admitted to candidacy, students must have completed at least 18 credits at Washington University, have an overall GPA equal to or greater than 3.25, and pass the qualifying examination. All students are required to enroll in the department seminar every semester to receive passing grades. The first year students must complete the core curriculum, perform two research rotations, and find a permanent research adviser. Then, within 18 months after the qualifying exam (generally in their third year), students should defend their thesis proposal.

After the successful proposal defense, students should provide the research updates through annual meetings or reports with their thesis committee until their graduation. While conducting doctoral research, students should perform professionally in a research lab including compliance with safety and regulatory requirements for their research project. During the doctoral program, students must satisfy their fundamental and advanced teaching requirements by serving as a teaching assistant or assist in some teaching activity in the department for two or three semesters, by attending one of the TA-training workshops offered by the Teaching Center, and by presenting at least two formal presentations at the local level or at a national or international conference. Upon completion of the thesis, students must present the thesis in a public forum and successfully defend the thesis before their thesis committee.

For more detailed guidelines, please refer to the EECE doctoral studies handbook available on the EECE Graduate Degree Programs (http://eece.wustl.edu/graduateprograms) webpage.

Master of Engineering (MEng) in Energy, Environmental & Chemical Engineering

This 12-month professional graduate degree is a master's program based in course work for students interested in state-of-the-art practice in environmental engineering, energy systems, and chemical engineering. The master's degree provides students with critical scientific and engineering skill sets; leadership training for management, economics, and policy decision; and the opportunity to specialize in specific pathways. The curriculum is geared to enhance skill sets for practice in industry.

The program consists of 30 units, with a total of six required core courses in five areas:

- Technical Core (6 units)

- Social, Legal, and Policy Aspects (3 units)
- Mathematics (3 units)
- Entrepreneurship or Leadership Training (3 units)
- Project Management (3 units)

Elective courses (400-level) are selected with the approval of the academic adviser.

Pathways comprised of specific elective courses can be completed to result in a certificate of specialization. Available pathways follow:

- Advanced Energy Technologies
- Environmental Engineering Science
- Technology for Environmental Health & International Development
- Energy and Environmental Nanotechnology
- Energy and Environmental Management

For more detailed information, please visit the MEng in EECE (http://eece.wustl.edu/graduateprograms/Pages/ms-ee.aspx) webpage.

Combined MEng/MBA (given jointly with Olin Business School)

In recent years, student interest has grown rapidly in the intersection between engineering and business approaches to issues of sustainability, energy, the environment, and corporate social responsibility. An interdisciplinary approach is necessary to address these issues with innovative, critical thinking, leading to practical, effective solutions. This combined program, the Master of Engineering in Energy, Environmental & Chemical Engineering/Master of Business Administration (MEng/MBA), between the School of Engineering & Applied Science and Olin Business School is well positioned to address this critical intersection.

The Olin MBA curriculum offers a comprehensive set of required and elective courses built upon a foundation of critical-thinking and leadership skills. Olin MBAs are able to shape the curriculum to meet their unique personal objectives, incorporating the MEng degree requirements.

Both MEng and MBA degrees will be awarded simultaneously at the completion of the program.

Please visit the Olin Combined Programs (http://www.olin.wustl.edu/EN-US/academic-programs/full-time-MBA/academics/joint-degrees/Pages/wash-u-graduate-programs.aspx) webpage for details.

Courses

Visit https://courses.wustl.edu to view semester offerings for E44 EECE (https://courses.wustl.edu/CourseInfo.aspx?sch=E&dept=E44&crslvl=5:8).

E44 EECE 500 Independent Study
Independent investigation on topic of special interest. Interested students are encouraged to approach and engage faculty to develop a topic of interest. A form declaring the agreement must be filed in the departmental office. Petitions are generally considered in the semester preceding the independent study experience. Prerequisite: graduate-level standing.
Credit variable, maximum 9 units.

E44 EECE 501 Transport Phenomena in EECE
The aim of the course is for students to develop skills in applying principles of momentum, heat and mass transport in an unified manner to problems encountered in the areas of energy, environmental and chemical processes. A systems approach is followed so that the general principles can be grasped, and the skills to develop mathematical models of seemingly different processes are emphasized. This provides the students with a general tool which they can apply later in their chosen field of research. (Prior to FL2015, this course was numbered: E33 501.)
Credit 3 units.

E44 EECE 502 Advanced Thermodynamics in EECE
The objective of this course is to understand classical thermodynamics at a deeper level than is reached during typical undergraduate work. Emphasis is placed on solving problems relevant to chemical engineering materials science. Prerequisite: E63 ChE 320 or E44 203 or equivalent. (Prior to FL2015, this course was numbered: E33 511.)
Credit 3 units.

E44 EECE 503 Mathematical Methods in EECE
The course introduces students to mathematical principles essential for graduate study in any engineering discipline. Applied mathematical concepts are demonstrated by applications to various areas in energy, environmental, biomedical, chemical, mechanical, aerospace, electrical and civil engineering. (Prior to FL2015, this course was numbered: E33 502.)
Credit 3 units.

E44 EECE 504 Aerosol Science and Technology
Fundamental properties of particulate systems — physics of aerosols, size distributions, mechanics and transport of particles: diffusion, inertia, external force fields. Visibility and light scattering. Aerosol dynamics — coagulation, nucleation, condensation. Applications to engineered systems: Nanoparticle synthesis, atmospheric aerosols, combustion aerosols, pharmaceutical aerosols. Prerequisites: EECE 301, ESE 317 or ESE 318 and 319. (Prior to FL2015, this course was numbered: E63 518.)
Credit 3 units. EN: TU

E44 EECE 505 Aquatic Chemistry
Aquatic chemistry governs aspects of the biogeochemical cycling of trace metals and nutrients, contaminant fate and transport, and the performance of water and wastewater treatment processes. This course examines chemical reactions relevant to natural and engineered aquatic systems. A quantitative approach emphasizes the solution of chemical equilibrium and kinetics problems. Topics covered include chemical equilibrium and kinetics, acid-base equilibria and alkalinity, dissolution and precipitation of solids, complexation of metals, oxidation-reduction processes, and reactions on solid surfaces. A primary

objective of the course is to be able to formulate and solve chemical equilibrium problems for complex environmental systems. In addition to solving problems manually to develop chemical intuition regarding aquatic systems, software applications for solving chemical equilibrium problems are also introduced. Prerequisite: Chem 112A. (Prior to FL2015, this course was numbered: E33 443/543.)
Credit 3 units. EN: TU

E44 EECE 506 Bioprocess Engineering I: Fundamentals & Applications
The course covers the fundamentals and provides the basic knowledge needed to understand and analyze processes in biotechnology in order to design, develop and operate them efficiently and economically. This knowledge is applied to understand various applications and bioprocesses, such as formation of desirable bio and chemical materials and products, production of bioenergy, food processing and waste treatment. The main objective of the course is to introduce the essential concepts and applications of bioprocessing to students of diverse backgrounds. An additional project is required to obtain graduate credit. Prerequisites: L41 Biol 2960 or equivalent or permission of instructor. (Prior to FL2015, this course was numbered: E63 453/553.)
Credit 3 units. EN: TU

E44 EECE 507 Kinetics and Reaction Engineering Principles
The course is aimed at a modern multiscale treatment of kinetics of chemical and biochemical reactions and application of these fundamentals to analyze and design reactors. Application of reaction engineering principles in the areas related to energy generation, pollution prevention, chemical and biochemical processes are studied and illustrated with case studies and computer models. Description of the role of mass and heat transport in reacting systems is also provided with numerous examples. (Prior to FL2015, this course was numbered: E33 503.)
Credit 3 units.

E44 EECE 508 Research Rotation
First-year doctoral students in EECE should undertake research rotation as a requirement prior to choosing a permanent research adviser. The rotation requires the student to work under the guidance of a faculty member. (Prior to FL2015, this course was numbered: E33 508.)

E44 EECE 509 Seminar in Energy, Environmental, and Chemical Engineering
All graduate students in EECE should attend the Departmental Seminar Series to gain exposure in various diverse fields of research. Students are also expected to participate in journal clubs and other discussion formats to discuss topical research areas. The course is required of all graduate students every semester of residency in the program. (Prior to FL2015, this course was numbered: E33 509.)
Credit 1 unit.

E44 EECE 510 Advanced Topics in Aerosol Science & Engineering
This course is focused on discussion of advanced topics in aerosol science and engineering and its applications in a variety of fields — materials science, chemical engineering, mechanical engineering, and environmental engineering. Prerequisite: EECE 504. (Prior to FL2015, this course was numbered: E63 592A.)
Credit 3 units. EN: TU

E44 EECE 512 Combustion Phenomena
Introduction to fundamental aspects of combustion phenomena including relevant thermochemistry, fluid mechanics, and transport processes. Emphasis is on elucidation of the physico-chemical processes, problem formulation, and analytical techniques. Topics covered include ignition, extinction, diffusion flames, particle combustion, deflagrations, and detonations. Prerequisites: Graduate standing or permission of instructor. (Prior to FL2015, this course was numbered: E33 5404.)
Credit 3 units. EN: TU

E44 EECE 513 Topics in Nanotechnology
This course is focused on the discussion of topics in nanotechnology — with a focus on nanoparticles and their applications in a variety of fields — materials science, chemical engineering, mechanical engineering, environmental engineering, medicine. (Prior to FL2015, this course was numbered: E63 526.)
Credit 3 units. EN: TU

E44 EECE 514 Atmospheric Science and Climate
This course covers current research topics in atmospheric chemistry and climate change. Topics include atmospheric composition, chemistry, transport, dynamics, radiation, greenhouse gases, natural and anthropogenic primary pollution sources and secondary aerosol production, and measurement techniques. Focus is placed on how our atmosphere and climate are altered in a world of changing energy production and land use. Prerequisites: Chemistry 112A, Physics 118 or 198, and junior or higher standing. (Prior to FL2015, this course was numbered: E33 547.)
Credit 3 units. EN: TU

E44 EECE 515 Dynamics of Air Pollution
Physicochemical processes governing the dynamics of pollutants from point and non-point sources: generation, transport and decay. Application of fundamental thermodynamics, mass/heat transfer and fluid mechanics principles to environmental systems. Prerequisites: EECE 203, ESE 317 or ESE 318 and 319, and EECE 505, or equivalent, or permission of instructor. (Prior to FL2015, this course was numbered: E63 510.)
Credit 3 units. EN: TU

E44 EECE 516 Measurement Techniques for Particle Characterization
The purpose of this course is to introduce students to the principles and techniques of particle measurement and characterization. Practical applications of particle technology include air pollution measurement, clean manufacturing of semiconductors, air filtration, indoor air quality, particulate emission from combustion sources and so on. The course focuses on (1) integral moment measurement techniques, (2) particle sizing and size distribution measuring techniques, and (3) particle composition measurement techniques. The related issues such as particle sampling and transportation, the instrument calibration, and particle standards also are covered. (Prior to FL2015, this course was numbered: E63 563.)
Credit 3 units. EN: TU

E44 EECE 518 Sustainable Air Quality

Introduction to sustainability and sustainable air quality. Systems science as an organizing principle for air quality management. Setting of air quality goals. Observing the status and trends. Establishing causal factors: energy use and chemical processing. Natural sources and variability. Corrective actions to reach air quality goals. Process design for emission reductions. Adoptive response to air pollution episodes. A web-based class project is conducted through the semester. (Prior to FL2015, this course was numbered: E63 549.)
Credit 3 units. EN: TU

E44 EECE 531 Environmental Organic Chemistry

Fundamental, physical-chemical examination of organic molecules (focused on anthropogenic pollutants) in aquatic (environmental) systems. Students learn to calculate and predict chemical properties that are influencing the partitioning of organic chemicals within air, water, sediments and biological systems. This knowledge is based on understanding intermolecular interactions and thermodynamic principles. Mechanisms of important thermochemical, hydrolytic, redox, and biochemical transformation reactions are also investigated, leading to the development of techniques (such as structure-reactivity relationships) for assessing environmental fate or human exposure potential. Prerequisite: Chem 112A. (Prior to FL2015, this course was numbered: E33 448/548.)
Credit 3 units. EN: TU

E44 EECE 533 Physical and Chemical Processes for Water Treatment

Water treatment is examined from the perspective of the physical and chemical unit processes used in treatment. The theory and fundamental principles of treatment processes are covered and are followed by the operation of treatment processes. Processes covered include gas transfer, adsorption, precipitation, oxidation-reduction, flocculation, sedimentation, filtration, and membrane processes. (Prior to FL2015, this course was numbered: E33 588.)
Credit 3 units. EN: TU

E44 EECE 534 Environmental Nanochemistry

This course involves the study of nanochemistry at various environmental interfaces, focusing on colloid, nanoparticle, and surface reactions. The course also (1) examines the thermodynamics and kinetics of nanoscale reactions at solid-water interfaces in the presence of inorganic or organic compounds and microorganisms; (2) investigates how nanoscale interfacial reactions affect the fate and transport of contaminants; (3) introduces multidisciplinary techniques for obtaining fundamental information about the structure and reactivity of nanoparticles and thin films, and the speciation or chemical form of environmental pollutants at the molecular scale; (4) explores connections between environmental nanochemistry and environmental kinetic analysis at larger scales. This course helps students attain a better understanding of the relationship between nanoscience/technology and the environment — specifically how nanoscience could potentially lead to better water treatments, more effective contaminated-site remediation, or new energy alternatives. (Prior to FL2015, this course was numbered: E33 534.)
Credit 3 units. EN: TU

E44 EECE 536 Computational Chemistry of Molecular and Nanoscale Systems

This course explores the structure, properties and reactivity of molecular and nanoscale systems in engineering using computational chemistry tools. The science behind density functional theory (DFT) calculations and molecular dynamics (MD) simulations is explained and applied in the context of multiscale modeling. Special emphasis is placed on solid-state materials and aqueous/biological systems found in engineering. Students are encouraged to apply the methods discussed in class to their own research topics. Prerequisites: EECE 203 and 204, or permission of the instructor. (Prior to FL2015, this course was numbered: E33 591.)
Credit 3 units. EN: TU

E44 EECE 551 Metabolic Engineering and Synthetic Biology

Synthetic Biology is a transformative view of biology from "observation approach" to "synthesis approach." It is a new "engineering" discipline and aims to make the engineering of new biological function predictable, safe and quick. It will pave a wide range of applications to transform our views on production of sustainable energy and renewable chemicals, environmental problems, and human disease treatments. The field intersects with Metabolic Engineering in areas such as the design of novel pathways and genetic circuits for product generation and toxic chemical degradation. In this course, the field and its basis are introduced. First, relevant topics in biology, chemistry, physics and engineering are covered. Second, students will participate in brain-storming and discussion on new biology-based systems. Last, students will design and present new synthetic biology systems to solve real-world problems. (Prior to FL2015, this course was numbered: E33 596A.) No prerequisite. Both undergrad and graduate students can take this course.
Credit 3 units.

E44 EECE 552 Biomass Energy Systems and Engineering

This course offers background in the organic chemistry, biology and thermodynamics related to understanding the conversion of biomass. In addition, it includes relevant topics relating to biomass feedstock origin, harvest, transportation, storage, processing and pretreatment along with matters concerning thermo- and biochemical conversion technologies required to produce fuels, energy, chemicals and materials. Also, various issues with respect to biomass characterization, economics and environmental impact are discussed. The main objective of the course is to introduce concepts central to a large-scale integrated biomass bioconversion system. (Prior to FL2015, this course was numbered: E33 495D/595D.)
Credit 3 units. EN: TU

E44 EECE 554 Molecular Biochemical Engineering

This course is set for junior-level graduate students to bridge the gap between biochemical engineering theory and academic research in bioengineering. It covers common molecular biotechnologies (molecular biology, microbiology, recombinant DNA technology, protein expression, etc.), biochemical models (enzyme catalysis, microbial growth, bioreactor, etc.) and bioengineering methodologies (protein engineering, expression control systems, etc.). These theories and technologies are introduced in a manner closely related to daily academic research or biochemical industry. Areas of application include biofuel and chemical production, drug discovery and biosynthesis, bioremediation, and environmental applications. This course also contains a lab section (20~30%) that requires

students to apply the knowledge learned to design experiments, learn basic experimental skills and solve current research problems. Prerequisites: EECE 101, Biol 2960, Biol 4810. (Prior to FL2015, this course was numbered: E33 595C.)
Credit 3 units. EN: TU

E44 EECE 556 Bioenergy
A broad overview of the flow of energy, captured from sunlight during photosynthesis, in biological systems, and current approaches to utilize the metabolic potentials of microbes and plants to produce biofuels and other valuable chemical products. An overall emphasis is placed on the use of large-scale genomic, transcriptomic and metabolomic datasets in biochemistry. The topics covered include photosynthesis, central metabolism, structure and degradation of plant lignocellulose, and microbial production of liquid alcohol, biodiesel, hydrogen & other advanced fuels. Course meets during the second half of the spring semester. Prerequisites: Biol 4810 or permission of instructor. (Prior to FL2015, this course was numbered: E33 4830/5830.)
Credit 2 units.

E44 EECE 571 Industrial and Environmental Catalysis
Major industrial and environmental catalytic processes. Principal theories of heterogeneous catalysis. Experimental methods and techniques used to develop modern catalytic systems. Examples from the petrochemical industry, automotive exhaust systems and industrial emissions abatement. Prerequisites: Chem 112, 262. (Prior to FL2015, this course was numbered: E63 525.)
Credit 3 units. EN: TU

E44 EECE 572 Advanced Transport Phenomena
Application of transport phenomena to complex industrial problems. Three-phase reactors. Surface tension driven flows. Micro- and macroscopic entropy balance. Irreversible thermodynamics. Multi-component mass transfer and separation processes. Pressure-driven transport. Membrane transport. Electrochemical systems. Chemical vapor deposition and plasma CVD. Prerequisites: EECE 501 or equivalent. (Prior to FL2015, this course was numbered: E63 514.)
Credit 3 units. EN: TU

E44 EECE 576 Chemical Kinetics and Catalysis
This course reflects the fast, contemporary progress being made in decoding kinetic complexity of chemical reactions, in particular heterogeneous catalytic reactions. New approaches to understanding relationships between observed kinetic behavior and reaction mechanism are explained. Present theoretical and methodological knowledge are illustrated by many examples taken from heterogeneous catalysis (complete and partial oxidation), combustion and enzyme processes. Prerequisite: senior or graduate student standing. (Prior to FL2015, this course was numbered: E33 598.)
Credit 3 units. EN: TU

E44 EECE 591 Energy and Buildings
There is a $2 trillion U.S. market in energy efficiency with paybacks of 4-5 years. This course is an introduction to energy use in the built environment and means and methods for evaluating and harvesting these financial benefits. It is based on fundamentals of energy usage in building systems. Building sciences for architectural envelope, heating and cooling systems, lighting and controls. Building/weather interaction and utility weather regression analyses. Building dynamics and rates of change in energy usage. Students work in groups to perform an energy audit for a building on campus. Prerequisite: senior or graduate student standing, or permission of instructor. (Prior to FL2015, this course was numbered: E33 495/595.)
Credit 3 units.

E44 EECE 593 Energy and Environment
This course sets out to instruct the student on how to understand decision-making regarding energy and the environment, and provides a unique educational experience, wherein the challenges and potential solutions to meeting future energy needs are clearly elucidated via lectures and experiential learning. Topics include: overview of energy and the environment and associated challenges; description of power generation from coal, natural gas, biomass, wind, solar, hydro, geothermal and nuclear; political, environmental and social considerations; regulations, economics, decision-making; students gain experience with software capable of analyzing renewable energy projects worldwide, from backyard to power-plant scale systems. (Prior to FL2015, this course was numbered: E33 500A.)
Credit 3 units.

E44 EECE 595 Principles of Methods of Micro and Nanofabrication
A hands-on introduction to the fundamentals of micro- and nanofabrication processes with emphasis on cleanroom practices. The physical principles of oxidation, optical lithography, thin film deposition, etching and metrology methods will be discussed, demonstrated and practiced. Students will be trained in cleanroom concepts and safety protocols. Sequential microfabrication processes involved in the manufacture of microelectronic and photonic devices will be shown. Training in imaging and characterization of micro- and nanostructures will be provided. Prerequisite: graduate or senior standing or permission of the instructor.
Same as E37 MEMS 5611
Credit 3 units. EN: TU

E44 EECE 597 EECE Project Management
An introduction to the theory and practice of engineering project management, with an emphasis on projects related to environmental protection and occupational health and safety. Topics include: project definition and justification; project evaluation and selection; financial analysis and cost estimation; project planning, including scheduling, resourcing and budgeting; project oversight, auditing and reporting; and effective project closure. Students will be introduced to commonly used project management tools and systems, such as work breakdown structures, network diagrams, Gantt charts, and project management software. Topics will also include project management in different organizational structures and philosophies; creating effective project teams; and managing projects in international settings. Prerequisites: enrolled in MEng program; senior or higher standing.
Credit 3 units.

E44 EECE 599 Master's Research
Credit variable, maximum 9 units.

E44 EECE 600 Doctoral Research
Credit variable, maximum 9 units.

E44 EECE 883 Master's Continuing Student Status

E44 EECE 884 Doctoral Continuing Student Status

E44 EECE 885 Master's Nonresident

E44 EECE 886 Doctoral Nonresident

Materials Science & Engineering

The Institute of Materials Science and Engineering (IMSE) at Washington University in St. Louis offers a truly interdisciplinary PhD in Materials Science & Engineering. Materials Science & Engineering is the interdisciplinary field focused on the development and application of new materials with desirable properties and microstructures. Disciplines in the physical sciences (chemistry, physics, etc.) and engineering fields (mechanical engineering, electrical engineering, biomedical engineering, etc.) frequently play a central role in developing the fundamental knowledge that is needed for materials studies. The discipline of Materials Science & Engineering integrates this knowledge and uses it to design and develop new materials and to match these with appropriate technological needs.

The IMSE is well positioned to address the needs of a student seeking a truly interdisciplinary experience. Established in 2013, the IMSE brings together more than 30 research groups in Arts & Sciences, the School of Engineering & Applied Science, and the Medical School. The IMSE works to integrate and expand the existing materials interests at Washington University by establishing and overseeing shared research and instrument facilities, creating partnerships with industry and national facilities, and setting up outreach activities.

Current focused areas of research and advanced graduate education within the IMSE include:

Plasmonics, Photonics, and Materials for Sensors and Imaging (http://imse.wustl.edu/research-plasmonics)

Computational Materials Science (http://imse.wustl.edu/research-computational)

Energy Harvesting and Storage (http://imse.wustl.edu/research-energy)

Structure, Properties, and Phase Transformations of Complex Materials (http://imse.wustl.edu/research-glasses)

Environmental Technologies and Sustainability (http://imse.wustl.edu/research/environmental-technologies-and-sustainability)

Contact:	Beth Gartin
Phone:	314-935-7191
Email:	bgartin@wustl.edu
Website:	http://imse.wustl.edu

Faculty

Director

Kenneth F. Kelton (http://www.physics.wustl.edu/people/kelton_kenneth-f)
Arthur Holly Compton Professor of Arts & Sciences - Physics
PhD, Harvard University
Study and production of titanium-based quasicrystals and related phases. Fundamental investigations of time-dependent nucleation processes. Modeling of oxygen precipitation in single crystal silicon. Structure of amorphous materials. Relation between structure and nucleation barrier. Hydrogen storage in quasicrystals.

Associate Director

Katharine M. Flores (https://engineering.wustl.edu/Profiles/Pages/Kathy-Flores.aspx)
Professor - Mechanical Engineering & Materials Science
PhD, Stanford University
Professor Flores' primary research interest is the mechanical behavior of structural materials, with particular emphasis on understanding structure-processing-property relationships in bulk metallic glasses and their composites.

Professors

Sophia E. Hayes (http://www.chemistry.wustl.edu/people/primary-faculty/sophia-e-hayes)
Professor - Chemistry
PhD, University of California, Santa Barbara
Physical inorganic chemistry; materials chemistry; solid-state NMR; magnetic resonance; optically-pumped NMR (OPNMR); semiconductors; quantum wells; magneto-optical spectroscopy; quadrupolar NMR of thin films and tridecameric metal hydroxide clusters and thin films; carbon capture, utilization and storage (CCUS); CO2 geosequestration; CO2 capture; in situ NMR; metal carbonate formation.

Lan Yang (https://engineering.wustl.edu/Profiles/Pages/Lan-Yang.aspx)
Edwin H. & Florence G. Skinner Professor - Electrical & Systems Engineering
PhD, California Institute of Technology
Professor Yang's research interests are fabrication, characterization, and fundamental understanding of advanced nano/micro photonic devices with outstanding optical properties. Currently, her group focuses on the silicon-chip based ultra-high-quality micro-resonators made from spin-on glass. The spin-on glass is a kind of glass obtained by curing a special liquid using sol gel or wet chemical synthesis to form a layer of glass. The main advantage of the spin-on glass is the easy tailoring of the nano/micro structure of the glass by controlled variation in the precursor solutions. It enables them to fabricate various micro/nano photonic devices from advanced materials with desired properties.

Associate Professors

Young-Shin Jun (https://engineering.wustl.edu/Profiles/Pages/Young-Shin-Jun.aspx)
Harold D. Jolley Career Development Associate Professor - Energy, Environmental & Chemical Engineering
PhD, Harvard University
Professor Jun's research is highly interdisciplinary as the Jun group seeks to enable more environmentally sustainable CO2 sequestration as a mitigation technique for climate change. The group also develops nanochemistry-enabled new treatment techniques and catalysts for purifying drinking water and remediating contaminated water and soil, benefiting water reuse, managed aquifer recharge, and reverse osmosis processes.
In addition, the ENCL investigates biomineralization and bio-inspired chemistry for novel materials development.

Srikanth Singamaneni (https://engineering.wustl.edu/Profiles/Pages/Srikanth-Singamaneni.aspx)
Associate Professor - Mechanical Engineering & Materials Science
PhD, Georgia Institute of Technology
Professor Singamaneni's research interests include plasmonic engineering in nanomedicine (in vitro biosensing for point-of-care diagnostics, molecular bioimaging, nanotherapeutics), photovoltaics (plasmonically enhanced photovoltaic devices), surface enhanced Raman scattering (SERS) based chemical sensors with particular emphasis on the design and fabrication of unconventional and highly efficient SERS substrates, hierarchical organic/inorganic nanohybrids as multifunctional materials, bioinspired structural and functional materials, polymer surfaces and interfaces, responsive and adaptive materials and scanning probe microscopy and surface force spectroscopy of soft and biological materials.

Assistant Professors

Parag Banerjee (https://engineering.wustl.edu/Profiles/Pages/Parag-Banerjee.aspx)
Assistant Professor - Mechanical Engineering & Materials Science
PhD, University of Maryland, College Park
Professor Banerjee's research interests focus on two aspects of materials science and engineering. First, he is interested in the synthesis of nanomaterials with tunable properties using principles of self-assembly and self-limited reactions. Second and perhaps more importantly, he is interested in integrating these materials into "performance enhancing" nano-architectures for components such as biomedical sensors, energy storage, and energy harvesting devices.

Mikhail Y. Berezin (http://dbbs.wustl.edu/faculty/Pages/faculty_bio.aspx?SID=6263)
Assistant Professor - Radiology
PhD, Moscow Institute of Oil and Gas / Institute of Organic Chemistry
Professor Berezin's research interest lies in the investigation and application of molecular excited states and their reactions for medical imaging and clinical treatment. Excited states are the cornerstone of a variety of chemical, physical, and biological phenomena. The ability to probe, investigate, and control excited states is one of the largest achievements of modern science. The lab focuses on the development of novel optically active probes ranging from small molecules to nanoparticles, and the development of optical instrumentation for spectroscopy and imaging and their applications in medicine.

Julio D'Arcy (http://www.chemistry.wustl.edu/faculty/darcy)
Assistant Professor - Chemistry
PhD, University of California, Los Angeles
The overarching goals of the D'Arcy laboratory are to discover and apply novel functional nanostructured organic and inorganic materials utilizing universal synthetic chemistry protocols that control chemical structure, nanoscale morphology, and intrinsic properties. We are interested in capacitive and pseudocapacitive nanostructured materials such as conducting polymers, metal oxides, and carbon allotropes possessing enhanced chemical and physical properties, i.e., charge carrier transport, ion transport, surface area, thermal and mechanical stability.
Our concerted material discovery process is a multi-pronged approach; organic and inorganic nanostructured materials are synthesized via solution processing, electrochemistry, vapor phase deposition, and combinations thereof. Alternatively, we also develop self-assembly techniques that result in tailored materials.

Erik Henriksen (https://www.physics.wustl.edu/people/henriksen_erik)
Assistant Professor - Physics
PhD, Columbia University
We are an experimental condensed matter research lab with interests primarily in the quantum electronic properties of graphene and other novel two-dimensional systems. We utilize state-of-the-art nanofabrication techniques in combination with measurements made at low temperatures and high magnetic fields to explore both the fundamental electronic structures and emergent quantum phenomena of low-dimensional materials.

Cynthia Lo (https://engineering.wustl.edu/Profiles/Pages/Cynthia-Lo.aspx)
Assistant Professor - Energy, Environmental & Chemical Engineering
PhD, Massachusetts Institute of Technology
Professor Lo uses electronic structure calculations and molecular dynamics simulations to study the structure and reactivity of molecular and nanoscale systems for solar energy utilization. Some applications of current interest include bio-hybrid solar cells, photosynthesis, transparent conducting oxides for photovoltaic and thermoelectric applications, and multifunctional heterogeneous catalysts and photocatalysts. In addition, Professor Lo is interested in developing multiscale computational methods that link existing methods across time and length scales in order to model complex chemical systems.

Rohan Mishra (https://engineering.wustl.edu/Profiles/Pages/Rohan-Mishra.aspx)
Assistant Professor - Mechanical Engineering & Materials Science
PhD, The Ohio State University
In his lab at Washington University, Mishra plans to identify and develop a quantitative measure of structure-property correlations in materials, such as epitaxial thin films and materials with reduced dimensionality, using a synergistic combination of scanning transmission electron microscopy and atomic-scale theory, to create rational design of materials with properties tailored for electronic, magnetic, optical and energy applications.

Bryce Sadtler (http://www.chemistry.wustl.edu/faculty/sadtler)
Assistant Professor - Chemistry
PhD, University of California, Berkeley
The Sadtler research group seeks to understand and control structure-property relationships in adaptive, mesostructured materials. Through hierarchical design of the atomic composition, nanoscale morphology, and mesoscale organization of the individual components, we can direct the emergent chemical reactivity and physical properties of these complex systems. Research projects combine solution phase growth techniques to synthesize inorganic materials, external fields to control the growth and assembly of mesoscale architectures, and super-resolution imaging to provide spatiotemporal maps of the optical response and photocatalytic activity during the morphological evolution of these structures. Knowledge gained from these fundamental studies will be used to create functional materials, including plasmonic substrates that enhance absorption in thin-film semiconductors, mesostructured photocatalysts for solar fuels generation, and chemical sensors based on self-assembled photonic structures.

Simon Tang (http://www.orthoresearch.wustl.edu/content/Laboratories/3043/Simon-Tang/Tang-Lab/Overview.aspx)
Assistant Professor - Orthopaedics
PhD, Rensselaer Polytechnic Institute
With the overall theme of understanding the biological regulation of skeletal matrix quality, our research group integrates engineering and biology approaches for (1) understanding the effect of disease mechanisms on the structure-function relationships of skeletal tissues and (2) developing of translatable therapeutic and regenerative strategies for these diseases. The investigation of these scientific questions includes the application of finite element analyses, multiscale tissue mechanics, and the functional imaging of skeletal tissues for regenerative medicine with in vitro and in vivo biological systems.

Elijah Thimsen (https://engineering.wustl.edu/Profiles/Pages/Elijah-Thimsen.aspx)
Assistant Professor - Energy, Environmental & Chemical Engineering
PhD, Washington University
The Interface Research Group focuses on advanced gas-phase synthesis of nanomaterials for energy applications. We are currently exploring nonthermal plasma synthesis and atomic layer deposition (ALD). The goal is to discover and then understand useful interfacial phenomena. Examples of applications we are currently interested in are: transparent conducting oxides, photovoltaics, lithium-sulfur batteries, and coatings for high-temperature combustion.

Fuzhong Zhang (https://engineering.wustl.edu/Profiles/Pages/Fuzhong-Zhang.aspx)
Assistant Professor - Energy, Environmental & Chemical Engineering
PhD, University of Toronto
Professor Zhang's research interests focus on developing synthetic biology approaches to produce advanced biofuels, chemicals, and materials from sustainable resources. Current research projects include: (1) developing dynamic regulatory systems for biosynthetic pathways; (2) engineering microbes to produce structure-defined biofuels and chemicals; (3) developing microbial factories for advanced materials; (4) engineering cyanobacteria for synthetic biology applications.

Degree Requirements

Interdisciplinary PhD in Materials Science & Engineering

To earn a PhD degree, students must complete the Graduate School requirements, along with specific program requirements. Course work includes:

- Four IMSE Core Courses (12 academic credits)

Code	Title	units
MEMS 5601	Mechanical Behavior of Materials	3
MEMS 5608	Introduction to Polymer Science and Engineering	3
MEMS 5610	Quantitative Materials Science and Engineering	3
Physics 537	Thermodynamics & Kinetics of Materials	3
Total units		12

- Solid State Chemistry or Physics (3 academic credits)

Code	Title	units
Chem 465	Solid-State and Materials Chemistry	3
or Physics 472	Solid State Physics	

- IMSE 500 First-Year Research Rotation (3 academic credits)
- IMSE 501 Seminar (1 academic credit; 2 required, 3 allowed for credit)
- Three courses (9 credits) from a preapproved list of Materials Science & Engineering electives
- Additional electives from participating departments to reach 36 academic credits (~9 academic credits, ~3 courses)
- A maximum of 12 credits of 400-level courses may be applied to the required 36 academic credits

Students must maintain an average grade of B (GPA 3.0) for all 72 credits. Additionally, the required courses must be completed with no more than one grade below a B-. Up to 24 graduate credits may be transferred with the approval of the Graduate Studies Committee, chaired by the Associate Director of the IMSE.

In addition to fulfilling the course and research credit requirements, the student must:

- Complete a Research Rotation
- Identify an IMSE faculty member willing and able to support the student's thesis research on a materials-related topic
- Fulfill the Teaching Requirement
  - Attend 2+ Teaching Center Workshops
  - 15 units of teaching experience (basic and advanced levels)
- Successfully complete the Qualifying Examination (oral and written)
- Maintain satisfactory research progress, as determined by the student's thesis adviser and mentoring committee
- Successfully complete the Thesis Proposal and Presentation
- Successfully complete and defend a dissertation

Failure to meet these requirements will result in dismissal from the program.

Course Plan

Year 1

Fall Semester (13 credits)

- Solid-State and Materials Chemistry (Chem 465) or elective
- Quantitative Materials Science and Engineering (MEMS 5610)
- Mechanical Behavior of Materials (MEMS 5601)
- Elective
- IMSE Seminar

Spring Semester (13 credits)

- Thermodynamics & Kinetics of Materials (Physics 537)
- Introduction to Polymer Science and Engineering (MEMS 5608)
- Solid State Physics (Physics 472) or elective
- IMSE First-Year Research Rotation
- IMSE Seminar Series

Summer

- Begin thesis research
- Prepare for Quailfying Exam (August)
  - Written document and oral presentation on research rotation
  - Oral exam on fundamentals from core courses

Years 2 and beyond

- 3 electives (discuss with PhD adviser)
- IMSE Seminar (once more for credit)
- IMSE PhD Research

- Teaching Requirement
  - Attend 2+ Teaching Center Workshops
  - 15 units of teaching experience (basic and advanced levels)
- Annual (or more frequent) meetings with Faculty Mentoring Committee
- Thesis proposal and presentation (fifth semester)
- Dissertation and oral defense

Mechanical Engineering & Materials Science

The Department of Mechanical Engineering & Materials Science offers a **PhD** in either **Mechanical Engineering** or **Aerospace Engineering**. The department's research strengths include biomechanics, materials, energy, fluid mechanics, and rotary-wing aerodynamics. The doctoral student works in conjunction with his or her adviser in designing the program of study and research project. The dissertation is defended at the end of the research effort. A typical time to PhD after an undergraduate engineering degree is four to five years, but the length of program may vary, depending on the individual and the area of study.

The Department of Mechanical Engineering & Materials Science offers an **MS** degree in either **Mechanical Engineering, Aerospace Engineering,** or **Materials Science and Engineering**. The department also offers a **Master of Engineering in Mechanical Engineering** for those coming from fields closely related to mechanical engineering. The MS degrees can be done either as a course option or a thesis option. For the thesis option, the student will work closely with a faculty adviser on the thesis project. Typical time for an MS or MEng degree is one and one-half to two years, with the thesis option usually taking longer than the course option.

Contact for the PhD program: Prof. Jessica Wagenseil, jessica.wagenseil@wustl.edu

Contact for the MS program: Prof. David Peters, dap@wustl.edu

Website:	http://mems.wustl.edu

Faculty

Chair

Philip V. Bayly (https://engineering.wustl.edu/Profiles/Pages/Philip-Bayly.aspx)
Lilyan and E. Lisle Hughes Professor of Mechanical Engineering
PhD, Duke University
Nonlinear dynamics, vibrations, biomechanics

Associate Chairs

Katharine M. Flores (Materials Science) (https://engineering.wustl.edu/Profiles/Pages/Kathy-Flores.aspx)
PhD, Stanford University
Mechanical behavior of structural materials

Kenneth L. Jerina (Mechanical Engineering) (https://engineering.wustl.edu/Profiles/Pages/Kenneth-Jerina.aspx)
Earl E. and Myrtle E. Walker Professor of Engineering
DSc, Washington University
Materials, design, solid mechanics, fatigue and fracture

Endowed Professors

Ramesh K. Agarwal (https://engineering.wustl.edu/Profiles/Pages/Ramesh-Agarwal.aspx)
William Palm Professor of Engineering
PhD, Stanford University
Computational fluid dynamics and computational physics

Thomas G. Harmon (https://engineering.wustl.edu/Profiles/Pages/Thomas-Harmon.aspx)
Clifford W. Murphy Professor
PhD, Massachusetts Institute of Technology
Reinforced and prestressed concrete, structural design, fiber reinforced polymers

Mark J. Jakiela (https://engineering.wustl.edu/Profiles/Pages/Mark-Jakiela.aspx)
Lee Hunter Professor of Mechanical Design
PhD, University of Michigan
Mechanical design, design for manufacturing, optimization, evolutionary computation

David A. Peters (https://engineering.wustl.edu/Profiles/Pages/David-Peters.aspx)
McDonnell Douglas Professor of Engineering
PhD, Stanford University
Aeroelasticity, vibrations, helicopter dynamics

Shankar M.L. Sastry (https://engineering.wustl.edu/Profiles/Pages/Shankar-Sastry.aspx)
Christopher I. Byrnes Professor of Engineering
PhD, University of Toronto
Materials science, physical metallurgy

Professor

Guy M. Genin (https://engineering.wustl.edu/Profiles/Pages/Guy-Genin.aspx)
PhD, Harvard University
Solid mechanics, fracture mechanics

Associate Professors

Srikanth Singamaneni (https://engineering.wustl.edu/Profiles/Pages/Srikanth-Singamaneni.aspx)
PhD, Georgia Institute of Technology
Microstructures of cross-linked polymers

Jessica E. Wagenseil (https://engineering.wustl.edu/Profiles/Pages/Jessica-Wagenseil.aspx)
DSc, Washington University
Arterial biomechanics

Assistant Professors

Damena D. Agonafer
PhD, University of Illinois at Urbana-Champaign
Computational fluid dynamics and computational physics

Parag Banerjee (https://engineering.wustl.edu/Profiles/Pages/Parag-Banerjee.aspx)
PhD, University of Maryland
Materials sciences and engineering, nanostructured materials, materials synthesis, and novel devices for storing and harvesting energy

Spencer P. Lake (https://engineering.wustl.edu/Profiles/Pages/Spencer-Lake.aspx)
PhD, University of Pennsylvania
Soft tissue biomechanics

J. Mark Meacham (https://engineering.wustl.edu/Profiles/Pages/Mark-Meacham.aspx)
PhD, Georgia Institute of Technology
Micro-/Nanotechnologies for thermal systems and the life sciences

Rohan Mishra (https://engineering.wustl.edu/Profiles/Pages/Rohan-Mishra.aspx)
PhD, Ohio State University
Computational materials science

Amit Pathak (https://engineering.wustl.edu/Profiles/Pages/Amit-Pathak.aspx)
PhD, University of California, Santa Barbara
Cellular biomechanics

Professors of the Practice

Harold J. Brandon
DSc, Washington University
Energetics, thermal systems

Swami Karunamoorthy
DSc, Washington University
Helicopter dynamics, engineering education

Joint Faculty

Richard L. Axelbaum (EECE) (https://engineering.wustl.edu/Profiles/Pages/Richard-Axelbaum.aspx)
The Stifel & Quinette Jens Professor of Environmental Engineering Science
PhD, University of California, Davis
Combustion, nanomaterials

Elliot L. Elson (Biochemistry and Molecular Biophysics) (http://bmbweb.wustl.edu/faculty/faculty/elliot-elson)
Professor Emeritus of Biochemistry & Molecular Biophysics
PhD, Stanford University
Biochemistry and molecular biophysics

Kenneth F. Kelton (Physics) (http://www.physics.wustl.edu/people/kelton_kenneth-f)
Arthur Holly Compton Professor of Arts & Sciences
PhD, Harvard University
Study and production of titanium-based quasicrystals and related phases

Eric C. Leuthardt (Neurological Surgery and BME) (http://www.neurosurgery.wustl.edu/patient-care/find-a-physician/clinical-faculty/eric-c-leuthardt-md-250)
MD, University of Pennsylvania School of Medicine
Neurological surgery

Matthew J. Silva (Orthopaedic Surgery) (http://www.orthoresearch.wustl.edu/content/Laboratories/2963/Matthew-Silva/Silva-Lab/Overview.aspx)
Julia and Walter R. Peterson Orthopaedic Research Professor
PhD, Massachusetts Institute of Technology
Biomechanics of age-related fractures and osteoporosis

Larry A. Taber (BME) (https://engineering.wustl.edu/Profiles/Pages/Larry-Taber.aspx)
Dennis and Barbara Kessler Professor of Biomedical Engineering
PhD, Stanford University
Biomechanics, mechanics of development

Simon Tang (Orthopaedic Surgery, BME) (http://www.orthoresearch.wustl.edu/content/Laboratories/3043/Simon-Tang/Tang-Lab/Overview.aspx)
PhD, Rensselaer Polytechnic Institute
Biological mechanisms

Senior Professors

Phillip L. Gould
PhD, Northwestern University
Structural analysis and design, shell analysis and design, biomechanical engineering

Salvatore P. Sutera
PhD, California Institute of Technology
Viscous flow, biorheology

Barna A. Szabo
PhD, State University of New York–Buffalo
Numerical simulation of mechanical systems, finite-element methods

Lecturers

Emily J. Boyd
PhD, University of Texas at Austin
Thermo fluids

H. Shaun Sellers
PhD, Johns Hopkins University
Mechanics and materials

Louis G. Woodhams
BS, University of Missouri-St. Louis
Computer-aided design

Senior Research Associate

Ruth J. Okamoto
DSc, Washington University
Biomechanics, solid mechanics

Research Assistant Professor

Anupriya Agrawal
PhD, Ohio State University
Materials science

Adjunct Instructors

Ricardo L. Actis
DSc, Washington University
Finite element analysis, numerical simulation, aircraft structures

Robert G. Becnel
MS, Washington University
FE Review

John D. Biggs
MEng, Washington University
Thermal science

Andrew W. Cary
PhD, University of Michigan
Computational fluid dynamics

Dan E. Driemeyer
PhD, University of Illinois
Thermo science

Richard S. Dyer
PhD, Washington University
Propulsion, thermodynamics, fluids

John M. Griffith
BS, Washington University
Manufacturing

Hanford Gross
BS, Washington University
Engineering project management

Jason Hawks
MS, Washington University
Structural analysis

James P. Howe
MS, Washington University
Thermo systems design

Richard R. Janis
MS, Washington University
Building environmental systems

Adetunji Onikoyi
PhD, University of California, Santa Barbara
Thermo sciences

Rigoberto Perez
PhD, Purdue University
Fatigue and fracture

Dale M. Pitt
DSc, Washington University
Aeroelasticity

Gary D. Renieri
PhD, Virginia Polytechnic Institute and State University
Structural applications, composite materials

Hiroshi Tada
PhD, Lehigh University
Solid mechanics

Matthew J. Watkins
MS, Washington University
Finite elements

Michael C. Wendl
DSc, Washington University
Mathematical theory and computational methods in biology and engineering

Laboratory and Design Specialist

Mary K. Malast
DSc, Washington University
Materials science

Professors Emeriti

Wallace B. Diboll Jr.
MSME, Rensselaer Polytechnic Institute
Dynamics, vibrations, engineering design

Paul C. Paris
PhD, Lehigh University
Classical mechanics, solid mechanics, dynamics, fracture mechanics, stochastic processes

Degree Requirements

Please refer to the following sections for information about:

- Doctoral Degrees (p. 60)
- MS in Mechanical Engineering (p. 61)
- MS in Aerospace Engineering (p. 62)
- MS in Materials Science and Engineering (p. 62)
- MEng in Mechanical Engineering (p. 63)

PhD in Mechanical Engineering or Aerospace Engineering

Policies & Regulations

A key objective of the doctoral program is to promote cutting-edge multidisciplinary research and education in the areas of Mechanical Engineering & Materials Science. Students are selected for admission to the program by a competitive process, and they typically start in the fall semester. On arriving at Washington University in St. Louis, the student will be advised by the temporary adviser on all procedural issues. The student will choose a permanent adviser by the end of the first year of residency in the program.

The following is a brief summary of the requirements for doctoral students:

1. Pass the qualifying exams. Qualifying exams should be taken by the end of the third semester.
2. Prepare and defend a research proposal. The research proposal should be defended by the end of the fifth semester.
3. Write and successfully defend the doctoral dissertation.
4. Complete a minimum of **36** credits of course work, and a minimum of **24** credits of doctoral research; total of **72** credits to earn the PhD degree.
5. Satisfy the applicable teaching requirements of the Graduate School.

Degrees Offered

The Department of Mechanical Engineering & Materials Science (MEMS) offers the following doctoral degrees:

- PhD in Mechanical Engineering
- PhD in Aerospace Engineering
- DSc in Mechanical Engineering, Aerospace Engineering, or Materials Science

  The Doctor of Science (DSc) has similar requirements to the PhD but without the teaching requirement. For a list of differences, please refer to the Doctor of Science (DSc) section of our website (http://mems.wustl.edu/graduate/programs/Pages/default.aspx).

- One may also pursue a PhD in Materials Science — through the Institute of Materials Science & Engineering (IMSE) — but work with professors from the Department of Mechanical Engineering & Materials Science. For details on this program, visit the IMSE Graduate Program (http://imse.wustl.edu/program) webpage.

For more information on MEMS PhD degrees, visit the MEMS Graduate Degree Programs (https://mems.wustl.edu/graduate/programs/Pages/default.aspx) webpage.

MS in Mechanical Engineering (MSME)

Master of Science in Mechanical Engineering *Thesis Option*

The quantitative requirement for the degree is 30 credit hours. A minimum of 24 of these units must be course work, and a minimum of 6 units must be Master's Research (MEMS 599).

The overall grade-point average must be 2.70 or better.

Courses may be chosen from 400- and 500-level offerings. All must be engineering, math or science courses with the following restrictions:

- A maximum of 3 units of Independent Study (MEMS 500) are allowed.
- A maximum of 6 units of 400-level courses are allowed, and these must be from courses not required for the BSME degree (if counted for the MSAE) or not required for the BSAE degree (if counted for the MSME degree).
- Each course must be approved by the candidate's thesis adviser.
- A maximum of 6 units of transfer credit is allowed for courses taken at other graduate institutions, and these must have been taken with grade B or better.
- A minimum of 15 units of the total 30 units must be in MEMS courses.

The student must also write a satisfactory thesis and successfully defend it in an oral examination before a faculty committee consisting of at least three members, at least two of which are from the Department of Mechanical Engineering & Materials Science.

Full-time MS students in any area are required every semester to take MEMS 501 Graduate Seminar, which is a zero-unit, pass-fail course.

Master of Science in Mechanical Engineering *Course Option*

The quantitative requirement for the degree is 30 credit hours (normally 10 courses) completed with a grade point average of 2.70 or better.

Course programs may be composed from one area of specialization below (MSME) or in aerospace engineering (MSAE). They must conform to the following distribution:

Applied Mathematics	**6 credits**
Area of Specialization	**15 credits**
Electives	**9 credits**

Elective courses may be chosen in any area of engineering or mathematics at 400-level or higher. Of the 30 units, a minimum of 24 must be in 500-level courses. No more than 6 units may be in 400-level courses; but core requirements for the ME undergraduate degree are not allowed. A maximum of 3 credits of Independent Study, MEMS 400 or MEMS 500, may be used as an elective. A minimum of 15 units must be in MEMS. Non-engineering courses (such as T-courses or finance and entrepreneurship) cannot be counted. Full-time MS students in any area are required every semester to take MEMS 501 Graduate Seminar, which is a zero-unit, pass-fail course.

Degree candidates will plan their course programs with the help of a departmental adviser. Use the links below to find courses in the areas of specialization.

Engineering Areas of Specialization for the MS in Mechanical Engineering

- Applied Mechanics (https://mems.wustl.edu/graduate/programs/Pages/MS-in-Mechanical-Engineering.aspx)
- Dynamics/Mechanical Design (https://mems.wustl.edu/graduate/programs/Pages/MS-in-Mechanical-Engineering.aspx)
- Solid Mechanics/Materials Science (https://mems.wustl.edu/graduate/programs/Pages/MS-in-Mechanical-Engineering.aspx)
- Fluid/Thermal Sciences (https://mems.wustl.edu/graduate/programs/Pages/MS-in-Mechanical-Engineering.aspx)
- Energy Conversion and Efficiency (https://mems.wustl.edu/graduate/programs/Pages/specialized-tracks.aspx)
- Numerical Simulation in Solid Mechanics (https://mems.wustl.edu/graduate/programs/Pages/specialized-tracks.aspx)

MS in Aerospace Engineering (MSAE)

Master of Science in Aerospace Engineering *Thesis Option*

The quantitative requirement for the degree is 30 credit hours. A minimum of 24 of these units must be course work, and a minimum of 6 units must be Master's Research (MEMS 599).

The overall grade-point average must be 2.70 or better.

Courses may be chosen from 400- and 500-level offerings. All must be engineering, math or science courses with the following restrictions:

- A maximum of 3 units of Independent Study (MEMS 500) are allowed.
- A maximum of 6 units of 400-level courses are allowed, and these must be from courses not required for the BSME degree (if counted for the MSAE) or not required for the BSAE degree (if counted for the MSME degree).
- Each course must be approved by the candidate's thesis adviser.
- A maximum of 6 units of transfer credit is allowed for courses taken at other graduate institutions, and these must have been taken with grade B or better.
- A minimum of 15 units of the total 30 units must be in MEMS courses.

The student must also write a satisfactory thesis and successfully defend it in an oral examination before a faculty committee consisting of at least three members, at least two of which are from the Department of Mechanical Engineering & Materials Science.

Full-time MS students in any area are required every semester to take MEMS 501 Graduate Seminar, which is a zero-unit, pass-fail course.

Master of Science in Aerospace Engineering *Course Option*

The quantitative requirement for the degree is 30 credit hours (normally 10 courses) completed with a grade point average of 2.70 or better.

Course programs must be focused in the area of aerospace engineering. They must conform to the following distribution:

Applied Mathematics	**6 credits**
Aerospace	**15 credits**
Electives	**9 credits**

Elective courses may be used to accumulate additional credits in other areas of engineering or in mathematics. A maximum of 3 credits of Independent Study (MEMS 500) may be included as an elective course. A maximum of 6 units of 400-level courses (not required for a MEMS undergraduate degree) may also be included. Non-engineering courses (such as T-courses or finance and entrepreneurship) cannot be counted as engineering electives. A minimum of 15 units must be in MEMS.

Full-time MS students are required to take MEMS 501 Graduate Seminar, which is a zero-unit, pass-fail course.

Degree candidates will plan their course programs with the help of a departmental adviser.

MS in Materials Science and Engineering

Master of Science in Materials Science and Engineering *Thesis Option*

The quantitative requirement for the degree is 30 credit hours. A minimum of 24 of these units must be course work, and a minimum of 6 units must be Master's Research (MEMS 599).

The overall grade-point average must be 2.70 or better.

Courses are to be Engineering courses at the 500-level or above, or Chemistry or Physics courses at the 400-level or above, and course work must include 3 units (one course) of mathematics at the graduate level. The following restrictions apply:

- A maximum of 3 units of Independent Study (MEMS 500) are allowed.
- A maximum of 6 units of 400-level courses are allowed.
- Each course must be approved by the candidate's thesis adviser.
- A maximum of 6 units of transfer credit is allowed for courses taken at other graduate institutions, and these must have been taken with grade B or better.
- A minimum of 15 units of the total 30 units must be in MEMS courses.

The student must also write a satisfactory thesis and successfully defend it in an oral examination before a faculty committee consisting of at least three members, at least two of which are from the Department of Mechanical Engineering & Materials Science.

Full-time MS students in any area are required every semester to take MEMS 501 Graduate Seminar, which is a zero-unit, pass-fail course.

Master of Science in Materials Science and Engineering *Course Option*

The quantitative requirement for the degree is 30 credit hours (normally 10 courses) completed with a grade-point average of 2.70 or better.

Course work must include 18 units (six courses) from the following list as well as 3 units (one course) of mathematics at the graduate level. It is recommended that the student take at least one course from each from the following areas:

(A) Structure
(B) Characterization
(C) Properties
(D) Synthesis and Processing

Full-time MS students in any area are required every semester to take MEMS 501 Graduate Seminar, which is a zero-unit, pass-fail course.

MEng in Mechanical Engineering

Master of Engineering in Mechanical Engineering

The Master of Engineering in Mechanical Engineering (MEng in ME) is a one- to two-year program offered by the Department of Mechanical Engineering & Materials Science of Washington University in St. Louis. The program is especially tailored for: 1) individuals who plan to change careers and enter the ME profession; 2) international students seeking to establish U.S. credentials in the ME profession; and 3) current professionals working in mechanical engineering who wish to advance their skills and education. A distinctive feature of the program is the ability to customize the course content to meet specific individual needs.

Degree requirements are as follows:

Candidates for admission should have an undergraduate degree in engineering, the physical sciences or mathematics with a GPA of 2.75 or better.

It should be emphasized that, in many states, the MEng in ME will not be sufficient to qualify the degree recipient to sit for a Professional Engineering Exam.

- 30 units of credit in engineering or mathematics courses are required, and these must be at the 400-level or higher. Courses from the other engineering departments (CSE, EECE, ESE and BME) are encouraged. Washington University Continuing Education Courses (i.e., the T-courses or the U-courses) are not permitted.
- All courses must be taken for a grade, with an overall GPA of 2.70 or higher.
- At least 9 of the 30 units must be in MEMS courses at the 500-level. Allowed courses include Engineering Project Management (MEMS 5804).
- All 400-level courses must be either: 1) approved for the Master of Science Degree in ME or AE; or 2) approved by the MEMS faculty for application to the MEng degree.
- No more than 6 units of Independent Study are allowed.
- No more than 6 units may be transferred from another university, and these units must be in engineering or math courses at the 400-level or above, with a grade of B or better, and be courses not required for the candidate's BS degree.

Full-time MS students in any area are required every semester to take MEMS 501 Graduate Seminar, which is a zero-unit, pass-fail course.

Courses

Visit https://courses.wustl.edu to view semester offerings for E37 MEMS (https://courses.wustl.edu/CourseInfo.aspx?sch=E&dept=E37&crslvl=5:8).

E37 MEMS 500 Independent Study
Independent investigation on topic of special interest. Prerequisites: graduate standing and permission of the department chair. Students must complete the Independent Study Approval Form available in the department office.
Credit variable, maximum 6 units.

E37 MEMS 5001 Optimization Methods in Engineering
Analytical methods in design. Topics include: mathematical methods; linear and nonlinear programming; optimality criteria; fully stressed techniques for the design of structures and machine components; topological optimization; search

techniques; and genetic algorithms. Prerequisites: calculus and computer programming.
Credit 3 units. EN: TU

E37 MEMS 501 Graduate Seminar
This is a required pass/fail course for master's and doctoral degrees. A passing grade is required for each semester of full-time enrollment. A passing grade is received by attendance at the weekly seminars.

E37 MEMS 5101 Analysis and Design of Fluid-Power Systems
Design of hydraulic and pneumatic control and power systems using advanced concepts and analytical tools. Topics include: analysis of fluid flow through orifices and between parallel and inclined planes, theory of spool and flapper valves, feasibility, synthesis, analysis and applications of fluid systems, configuration of pumps, motors, fluid lines and valves, accumulators and storage devices, integration of components into systems, power systems, servo-systems, hydrostatic transmissions, performance diagrams using MATLAB and Simulink, design and analysis of fluid power systems.
Credit 3 units. EN: TU

E37 MEMS 5102 Materials Selection in Design
Analysis of the scientific bases of material behavior in the light of research contributions of the past 20 years. Development of a rational approach to the selection of materials to meet a wide range of design requirements for conventional and advanced applications. Although emphasis is placed on mechanical properties, acoustical, optical, thermal and other properties of interest in design are discussed.
Credit 3 units. EN: TU

E37 MEMS 5103 Advanced Machine Design
Advanced machine design topics including: stress, strain and strain energy in one dimension; applications to oil-well sucker rods, turbine, compressor and propeller and helicopter blades. Advanced beam theory applied to tie rods; beams on elastic foundation, hooks and curved bars. Helical, spiral and leaf springs. Design of thick cylinders, shrink fits and high-speed rotating disks. Analysis and design of circular and rectangular plates; effect of ribs. Torsion of shafting. Lubrication theory applied to bearings. High-speed ball bearings.
Credit 3 units. EN: TU

E37 MEMS 5201 Advanced Topics in Concrete Systems
Analysis and design of prestressed concrete members. Topics include: direct design of composite and noncomposite members for flexure, design of continuous beams, flexural strength, shear strength, and design of anchorage zone.
Credit 3 units. EN: TU

E37 MEMS 5202 Advanced Topics for Structural Systems
Advanced topics and current research on plastic design and analysis of space frames; plate and box girders; and torsion in structures. Prerequisite: permission of instructor.
Credit 3 units. EN: TU

E37 MEMS 5301 Nonlinear Vibrations
In this course, students are introduced to concepts in nonlinear dynamics and vibration and application of these concepts to nonlinear engineering problems. Specific topics include: modeling of lumped and continuous nonlinear systems (strings, beams and plates); vibrations of buckled structures; perturbation and other approximate analytical methods; the use and limitations of local linearization; properties of nonlinear behavior, such as dimension and Lyapunov exponents; stability of limit cycles; bifurcations; chaos and chaotic vibrations; experimental methods and data analysis for nonlinear systems. Concepts are reinforced with a number of examples from recently published research. Applications include aeroelastic flutter, impact dynamics, machine-tool vibrations, cardiac arhythmias and control of chaotic behavior.
Credit 3 units. EN: TU

E37 MEMS 5302 Theory of Vibrations
Analytical methods in vibrations. Topics include: Duhamel's integral, Laplace and Fourier transforms and Fourier series with applications to transient response, forced response and vibration isolation; Lagrange's equations for linear systems, discrete systems, degrees of freedom, reducible coordinates, holonomic constraints and virtual work; matrix methods and state variable approach with applications to frequencies and modes, stability and dynamic response in terms of real and complex modal expansions, dynamic response of continuous systems by theory of partial differential equations, Rayleigh-Ritz and Galerkin energy methods, finite difference and finite element algorithms.
Credit 3 units. EN: TU

E37 MEMS 5401 General Thermodynamics
General foundations of thermodynamics valid for small and large systems, and for equilibrium and nonequilibrium states. Topics include: definitions of state, work, energy, entropy, temperature, heat interaction and energy interaction. Applications to simple systems; phase rule; perfect and semi-perfect gas; bulk-flow systems; combustion, energy and entropy balances; availability analysis for thermo-mechanical power generation; and innovative energy-conversion schemes. Prerequisite: graduate standing or permission of instructor.
Credit 3 units. EN: TU

E37 MEMS 5402 Radiation Heat Transfer
Formulation of the governing equations of radiation heat transfer. Topics include: electromagnetic theory of radiation; properties of ideal and real surfaces; techniques for solutions of heat transfer between gray surfaces; radiation in absorbing, emitting and scattering media.
Credit 3 units. EN: TU

E37 MEMS 5403 Conduction and Convection Heat Transfer
This course examines heat conduction and convection through various fundamental problems that are constructed from the traditional conservation laws for mass, momentum and energy. Problems include the variable-area fin, the unsteady Dirichlet, Robbins and Rayleigh problems, multidimensional steady conduction, the Couette flow problem, duct convection and boundary layer convection. Though some numerics are discussed, emphasis is on mathematical technique and includes the extended power series method, similarity reduction, separation of variables, integral transforms, and approximate integral methods.
Credit 3 units. EN: TU

E37 MEMS 5404 Combustion Phenomena

Introduction to fundamental aspects of combustion phenomena including relevant thermochemistry, fluid mechanics and transport processes. Emphasis is on elucidation of the physico-chemical processes, problem formulation and analytical techniques. Topics covered include: ignition, extinction, diffusion flames, particle combustion, deflagrations and detonations. Prerequisite: graduate standing or permission of instructor.
Credit 3 units. EN: TU

E37 MEMS 5410 Fluid Dynamics I

Formulation of the basic concepts and equations governing a Newtonian, viscous, conducting, compressible fluid. Topics include: transport coefficients and the elements of kinetic theory of gases, vorticity, incompressible potential flow; singular solutions; flow over bodies and lifting surfaces; similarity method; viscous flow, boundary layer, low Reynolds number flows, laminar and turbulent flows.
Credit 3 units. EN: TU

E37 MEMS 5411 Fluid Dynamics II

Governing equations and thermodynamics relations for compressible flow. Topics include: kinetic theory of gases; steady, one-dimensional flows with friction and heat transfer; shock waves; Rankine-Hugoniot relations; oblique shocks; reflections from walls and flow interfaces, expansion waves, Prandtl-Meyer flow, flow in nozzles, diffusers and inlets, two-and three dimensional flows; perturbation methods; similarity rules; compressible laminar and turbulent boundary layers; acoustic phenomena. Emphasis is relevant to air vehicles.
Credit 3 units. EN: TU

E37 MEMS 5412 Computational Fluid Dynamics

Computational fluid dynamics relevant to engineering analysis and design. Topics include: fundamentals of finite-difference, finite-volume and finite-element methods; numerical algorithms for parabolic, elliptic and hyperbolic equations; convergence, stability and consistency of numerical algorithms; application of numerical algorithms to selected model equations relevant to fluid flow, grid-generation techniques and convergence acceleration schemes. Prerequisite: senior or graduate standing or permission of the instructor.
Credit 3 units. EN: TU

E37 MEMS 5413 Advanced Computational Fluid Dynamics

Scope and impact of computational fluid dynamics. Governing equations of fluid mechanics and heat transfer. Three-dimensional grid-generation methods based on differential systems. Numerical methods for Euler and compressible Navier-Stokes equation. Numerical methods for incompressible Navier-Stokes equations. Computation of transonic inviscid and viscous flow past airfoils and wings. Analogy between the equations of computational fluid dynamics, computational electromagnetics, computational aeroacoustics and other equations of computational physics. Non-aerospace applications — bio-fluid mechanics, fluid mechanics of buildings, wind and water turbines, and other energy and environment applications. Prerequisite: MEMS 5412 or permission of the instructor.
Credit 3 units. EN: TU

E37 MEMS 5414 Aeroelasticity and Flow-Induced Vibrations

This course deals with the interactions between aerodynamics, dynamics and structures in aerospace systems. Topics covered include unsteady aerodynamics, finite-state aerodynamic models, classical fixed-wing flutter, rotary-wing aeroelasticity and experimental methods in aeroelasticity. Emphasis is given to the prediction of flutter and limit cycles in aeroelastic systems.
Credit 3 units.

E37 MEMS 5415 Viscous Fluid Dynamics

Introduction to viscous flow phenomena; kinematic, transport and thermodynamic properties of liquids and gases; coefficients of viscosity, thermal conductivity and mass diffusion. Boundary conditions and equations of compressible, heat conducting viscous flow; dimensionless parameters. Navier-Stokes equations; transport of vorticity. Solutions for Newtonian fluids; channel and pipe flows, stagnation points. Laminar boundary layers; Blasius and Falkner-Skan flows. Reynolds analogy for heat transfer. Effects of wall suction or blowing, free shear flows, jets, wakes. Axisymmetric boundary layers, three-dimensional effects, separation. Linearized stability analysis of parallel viscous flows, Orr-Sommerfeld equations, inviscid Rayleigh instability. Effect of compressibility, Crocco-Busemann relation, recovery factor. Transition to turbulence, Tollmien-Schlichting waves, formation of turbulent spots, bypass transition. Stationary and nonstationary turbulent fluctuations, time-averaging, definitions of intensity and Reynolds' stresses. Equations for flat plate turbulent boundary layers, concepts of inner, outer and overlap layers, similarity in overlap layer, Cole's law of the wake. Integral relations for momentum and displacement thicknesses. Turbulent flows in channels and pipes, Moody chart. Turbulent jets and wakes. Effect of pressure gradient. Recovery factor in turbulent boundary layer flows.
Credit 3 units.

E37 MEMS 5416 Turbulence

Hydrodynamic instabilities and the origin of turbulence. Mixing length and vorticity transport theories. Statistical theories of turbulence. Phenomenological considerations of turbulence growth, amplification and damping, turbulent boundary layer behavior, and internal turbulent flow. Turbulent jets and wakes.
Credit 3 units. EN: TU

E37 MEMS 5420 HVAC Analysis and Design I

Fundamentals of heating, ventilating, and air conditioning — moist air properties, the psychrometric chart, classic moist air processes, design procedures for heating and cooling systems. Design of HVAC systems for indoor environmental comfort, health, and energy efficiency. Heat transfer processes in buildings. Development and application of techniques for analysis of heating and cooling loads in buildings, including the use of commercial software. Course special topics can include LEED rating and certification, cleanrooms, aviation, aerospace, and naval applications, ventilation loads, animal control facilities, building automation control, and on-site campus tours of state-of-the-art building energy and environmental systems.
Credit 3 units. EN: TU

E37 MEMS 5421 HVAC Analysis and Design II

Energy calculations to estimate the quantity of energy needed to heat and cool building structures. Fundamentals of incompressible flow, basics of centrifugal pump performance, and design procedures for water piping systems. Space air diffuser design to assure that temperatures, humidities and air velocities within occupied spaces are acceptable. Air duct design and fan analysis for optimally distributing air through building air duct systems. Performance analysis of refrigeration systems,

including the effects of pressure losses and heat transfer. Direct contact heat and mass transfer.
Credit 3 units. EN: TU

E37 MEMS 5422 Solar Energy Thermal Processes
Extraterrestrial solar radiation, solar radiation on Earth's surface, and weather bureau data. Review of selected topics in heat transfer. Methods of solar energy collection and solar energy storage. Transient and long-term solar system performance. Prerequisite: MEMS 342 or equivalent.
Credit 3 units. EN: TU

E37 MEMS 5423 Sustainable Environmental Building Systems
Sustainable design of building lighting and HVAC systems considering performance, life cycle cost and downstream environmental impact. Criteria, codes and standards for comfort, air quality, noise/vibration and illumination. Life cycle and other investment methods to integrate energy consumption/ conservation, utility rates, initial cost, system/component longevity, maintenance cost and building productivity. Direct and secondary contributions to acid rain, global warming and ozone depletion.
Credit 3 units. EN: TU

E37 MEMS 5424 Thermo-Fluid Modeling of Renewable Energy Systems
Overview of sustainable energy systems. Fundamentals of energy conversion. Renewable energy sources and energy conversion from wind, biomass, solar-thermal, geothermal and ocean/waves. Applications to energy storage, fuel cells, green air and ground transportation, energy-efficient buildings. Energy-economics modeling, emissions modeling, global warming and climate change.
Credit 3 units. EN: TU

E37 MEMS 5500 Elasticity
Elastic constitutive relations for isotropic and anisotropic materials. Formulation of boundary-value problems. Application to torsion, flexure, plane stress, plane strain and generalized plane stress problems. Solution of three-dimensional problems in terms of displacement potentials and stress functions. Solution of two-dimensional problems using complex variables and conformal mapping techniques. Variational and minimum theorems.
Credit 3 units. EN: TU

E37 MEMS 5501 Mechanics of Continua
A broad survey of the general principles governing the mechanics of continuous media. Topics include: general vector and tensor analysis, rigid body motions, deformation, stress and strain rate, large deformation theory, conservation laws of physics, constitutive relations, principles of continuum mechanics and thermodynamics, two-dimensional continua. Prerequisites: ESE 501–502 or instructor's permission.
Credit 3 units. EN: TU

E37 MEMS 5502 Plates and Shells
Introduction to the linear theory of thin elastic plates and shells. The emphasis is on application and the development of physical intuition. The first part of the course focuses on the analysis of plates under various loading and support conditions. The remainder of the course deals mainly with axisymmetric deformation of shells of revolution. Asymptotic methods are used to solve the governing equations. Applications to pressure vessels, tanks and domes. Prerequisites: BME 240 or MEMS 253; ESE 317 or equivalent.
Credit 3 units. EN: TU

E37 MEMS 5503 Structural Stability
Theorems of Equilibrium and Stability. Topics include: classification of instability phenomena, postbuckling behavior and imperfection-sensitivity, systems with multiple degrees of freedom, buckling of columns, beam-columns, and frames using classical and variational methods and stability and nonlinear behavior of plates and shells.
Credit 3 units. EN: TU

E37 MEMS 5504 Fracture Mechanics
Classical fracture and fatigue analysis and their limitations. Topics include: Griffith-Irwin, linear-elastic fracture-mechanics analysis, historical aspects, formulation of stability criteria, subcritical crack growth, anisotropic and inhomogeneous effects, fracture-control analysis, with applications to fracture-safety analysis relating to nuclear reactors, aircraft, rotating machinery, elastic-plastic fracture-mechanics analysis and future prospects and applications. Prerequisites: graduate standing or permission of instructor.
Credit 3 units. EN: TU

E37 MEMS 5506 Experimental Methods in Solid Mechanics
Current experimental methods to measure mechanical properties of materials are covered. Lectures include theoretical principles, measurement considerations, data acquisition and analysis techniques. Lectures are complemented by laboratory sections using research equipment such as biaxial testing machines, pressure myographs, indentation devices for different scales, and viscometers.
Credit 3 units. EN: TU

E37 MEMS 5507 Fatigue and Fracture Analysis
The course objective is to demonstrate practical methods for computing fatigue life of metallic structural components. The course covers the three major phases of metal fatigue progression: fatigue crack initiation, crack propagation and fracture. Topics include: stress vs. fatigue life analysis, cumulative fatigue damage, linear elastic fracture mechanics, stress intensity factors, damage tolerance analysis, fracture toughness, critical crack size computation and load history development. The course focus is on application of this technology to design against metal fatigue and to prevent structural failure.
Credit 3 units. EN: TU

E37 MEMS 5510 Finite Element Analysis
Theory and application of the finite element method. Topics include: basic concepts, generalized formulations, construction of finite element spaces, extensions, shape functions, parametric mappings, numerical integration, mass matrices, stiffness matrices and load vectors, boundary conditions, modeling techniques, computation of stresses, stress resultants and natural frequencies, and control of the errors of approximation. Prerequisite: graduate standing or permission of instructor.
Credit 3 units. EN: TU

E37 MEMS 5512 Composite Structures

Introduction to composite materials. Topics include: anisotropic elasticity and laminate theory; beams and columns of composite materials; plates and panels; transverse shear deformation effects; twisting and stretching shear coupling; honeycomb core sandwich panels; composite shells; energy methods for statics, stability and dynamics; hygrothermal effects; strength and failure theories.
Credit 3 units. EN: TU

E37 MEMS 5513 Computational Structural Mechanics

An introduction to the analysis and design of structures using finite elements. Topics include; elementary theory of elasticity, plate theories and buckling of plate structures, finite element formulation of 2-D elasticity and plate problems. Hands-on use of finite element software is emphasized. A major design project is included.
Credit 3 units. EN: TU

E37 MEMS 5515 Numerical Simulation in Solid Mechanics I

Solution of 2-D and 3-D elasticity problems using the finite element method. Topics include: linear elasticity; laminated material; stress concentration; stress intensity factor; solution verification; J integral; energy release rate; residual stress; multi-body contact; nonlinear elasticity; plasticity; and buckling. Prerequisite: graduate standing or permission of instructor.
Credit 3 units.

E37 MEMS 5516 Numerical Simulation in Solid Mechanics II

Solution of 2-D and 3-D elasticity problems using the finite element method. Topics include: laminates and composite materials; nonlinear elasticity; plasticity; incremental theory of plasticity; residual stress; geometric nonlinearity; membrane and bending load coupling; multi-body contact; stress intensity factor; interference fit; and buckling analysis. Prerequisite: graduate standing or permission of instructor.
Credit 3 units.

E37 MEMS 5520 Advanced Analytical Mechanics

Lagrange's equations and their applications to holonomic and nonholonomic systems. Topics include: reduction of degrees of freedom by first integrals, variational principles, Hamilton-Jacobi theory, general transformation theory of dynamics, applications such as theory of vibrations and stability of motion, and use of mathematical principles to resolve nonlinear problems. Prerequisite: senior or graduate standing or permission of instructor.
Credit 3 units. EN: TU

E37 MEMS 5560 Interfaces and Attachments in Natural and Engineered Structures

Attachment of dissimilar materials in engineering and surgical practice is a challenge. Bimaterial attachment sites are common locations for injury and mechanical failure. Nature presents several highly effective solutions to the challenge of bimaterial attachment that differ from those found in engineering practice. This course bridges the physiologic, surgical and engineering approaches to connecting dissimilar materials. Topics in this course are: natural bimaterial attachments; engineering principles underlying attachments; analysis of the biology of attachments in the body; mechanisms by which robust attachments are formed; concepts of attaching dissimilar materials in surgical practice and engineering; and bioengineering approaches to more effectively combine dissimilar materials.
Credit 3 units. EN: TU

E37 MEMS 5561 Mechanics of Cell Motility

A detailed review of biomechanical inputs that drive cell motility in diverse extracellular matrices (ECMs). This class discusses cytoskeletal machineries that generate and support forces, mechanical roles of cell-ECM adhesions, and regulation of ECM deformations. Also covered are key methods for cell level mechanical measurements, mathematical modeling of cell motility, and physiological and pathological implications of mechanics-driven cell motility in disease and development.
Credit 3 units.

E37 MEMS 5564 Orthopaedic Biomechanics-Cartilage/Tendon

Basic and advanced viscoelasticity and finite strain analysis applied to the musculoskeletal system, with a primary focus on soft orthopaedic tissues (cartilage, tendon and ligament). Topics include: mechanical properties of cartilage, tendon and ligament; applied viscoelasticity theory for cartilage, tendon and ligament; cartilage, tendon and ligament biology; tendon and ligament wound healing; osteoarthritis. This class is geared to graduate students and upper-level undergraduates familiar with statics and mechanics of deformable bodies. Prerequisites: BME 240 or equivalent. Note: BME 590Z (463/563) Orthopaedic Biomechanics—Bones and Joints is *not* a prerequisite.
Credit 3 units. EN: TU

E37 MEMS 5565 Mechanobiology of Cells and Matrices

At the interface of the cell and the extracellular matrix, mechanical forces regulate key cellular and molecular events that profoundly affect aspects of human health and disease. This course offers a detailed review of biomechanical inputs that drive cell behavior in physically diverse matrices. In particular, cytoskeletal force-generation machineries, mechanical roles of cell-cell and cell-matrix adhesions, and regulation of matrix deformations are discussed. Also covered are key methods for mechanical measurements and mathematical modeling of cellular response. Implications of matrix-dependent cell motility in cancer metastasis and embryonic development are discussed. Prerequisite: graduate standing or permission of the instructor
Credit 3 units. EN: TU

E37 MEMS 5601 Mechanical Behavior of Materials

A materials science-based study of mechanical behavior of materials with emphasis on mechanical behavior as affected by processes taking place at the microscopic and/or atomic level. The response of solids to external or internal forces as influenced by interatomic bonding, crystal/molecular structure, crystalline/noncrystalline defects and material microstructure are studied. The similarities and differences in the response of different kinds of materials viz., metals and alloys, ceramics, polymers and composites are discussed. Topics covered include physical basis of elastic, visco elastic and plastic deformation of solids; strengthening of crystalline materials; visco elastic deformation of polymers as influenced by molecular structure and morphology of amorphous, crystalline and fibrous polymers; deformation and fracture of composite materials; mechanisms of creep, fracture and fatigue; high strain-rate deformation of crystalline materials; and deformation of noncrystalline materials.
Credit 3 units. EN: TU

E37 MEMS 5602 Non-metallics
Structure, mechanical and physical properties of ceramics and cermets, with particular emphasis on the use of these materials for space, missile, rocket, high-speed aircraft, nuclear and solid-state applications.
Credit 3 units. EN: TU

E37 MEMS 5603 Materials Characterization Techniques I
An introduction to the basic theory and instrumentation used in transmission electron, scanning electron and optical microscopy. Practical laboratory experience in equipment operations, experimental procedures and material characterization.
Credit 3 units. EN: TU

E37 MEMS 5604 Materials Characterization Techniques II
Introduction to crystallography and elements of X-ray physics. Diffraction theory and application to materials science including following topics: reciprocal lattice concept, crystal-structure analysis, Laue methods, rotating crystal methods, powder method, and laboratory methods of crystal analysis.
Credit 3 units. EN: TU

E37 MEMS 5605 Mechanical Behavior of Composites
Analysis and mechanics of composite materials. Topics include micromechanics, laminated plate theory, hydrothermal behavior, creep, strength, failure modes, fracture toughness, fatigue, structural response, mechanics of processing, nondestructive evaluation, and test methods. Prerequisite: graduate standing or permission of the instructor.
Credit 3 units. EN: TU

E37 MEMS 5606 Soft Nanomaterials
Soft nanomaterials, which range from self-assembled monolayers (SAMs) to complex 3-D polymer structures, are gaining increased attention owing to their broad-range applications. The course introduces the fundamental aspects of nanotechnology pertained to soft matter. Various aspects related to the design, fabrication, characterization and application of soft nanomaterials are discussed. Topics covered include but are not limited to SAMs, polymer brushes, Layer-by-layer assembly, responsive polymers structures (films, capsules), polymer nanocomposites, biomolecules as nanomaterials and soft lithography.
Credit 3 units. EN: TU

E37 MEMS 5607 Introduction to Polymer Blends and Composites
The course covers topics in multicomponent polymer systems (polymer blends and polymer composites) such as: phase separation and miscibility of polymer blends, surfaces and interfaces in composites, microstructure and mechanical behavior, rubber toughened plastics, thermoplastic elastomers, block copolymers, fiber reinforced and laminated composites, techniques of polymer processing with an emphasis on composites processing, melt processing methods such as injection molding and extrusion, solution processing of thin films, selection of suitable processing methods and materials selection criteria for specific applications. Advanced topics include: nanocomposites such as polymer/CNT composites, bioinspired nanocomposites, and current research challenges. Prerequisite: MEMS 3610 or equivalent or permission of instructor.
Credit 3 units. EN: TU

E37 MEMS 5608 Introduction to Polymer Science and Engineering
Topics covered in this course are: the concept of long-chain or macromolecules, polymer chain structure and configuration, microstructure and mechanical (rheological) behavior, polymer phase transitions (glass transition, melting, crystallization), physical chemistry of polymer solutions (Flory-Huggins theory, solubility parameter, thermodynamics of mixing and phase separation), polymer surfaces and interfaces, overview of polymer processing (extrusion, injection molding, film formation, fiber spinning) and modern applications of synthetic and bio-polymers.
Credit 3 units. EN: TU

E37 MEMS 5609 Electronic Materials Processing
This course covers "unit processes" for manufacturing semiconductor chips. Topics include: crystal growth and doping of wafers, oxidation and diffusion, ion implantation, deposition, etching, cleaning and lithography. Processes are described with key concepts derived from science and engineering and process integration is covered for devices such as transistors and light emitting diodes. Nanoprocessing concepts are highlighted in the end to provide students with practical and advanced knowledge of semiconductor manufacturing. Prerequisites: undergraduate engineering mathematics, materials science and basic electronics or instructor's permission.
Credit 3 units. EN: TU

E37 MEMS 5610 Quantitative Materials Science and Engineering
Quantitative Materials Science and Engineering covers the mathematical foundation of primary concepts in materials science and engineering. Topics covered are: mathematical techniques in materials science and engineering; Fourier series; ordinary and partial differential equations; special functions; matrix algebra; and vector calculus. Each is followed by its application to concepts in: thermodynamics; kinetics and phase transformations; structure and properties of hard and soft matter; and characterization techniques. This course is intended especially for students pursuing graduate study in materials science.
Credit 3 units. EN: TU

E37 MEMS 5611 Principles and Methods of Micro and Nanofabrication
A hands-on introduction to the fundamentals of micro- and nanofabrication processes with emphasis on cleanroom practices. The physical principles of oxidation, optical lithography, thin film deposition, etching and metrology methods will be discussed, demonstrated and practiced. Students will be trained in cleanroom concepts and safety protocols. Sequential microfabrication processes involved in the manufacture of microelectronic and photonic devices will be shown. Training in imaging and characterization of micro- and nanostructures will be provided. Prerequisite: graduate or senior standing or permission of the instructor.
Credit 3 units. EN: TU

E37 MEMS 5700 Aerodynamics
Fundamental concepts of aerodynamics, equations of compressible flows, irrotational flows and potential flow theory,

singularity solutions, circulation and vorticity, Kutta-Joukowski theorem, thin airfoil theory, finite wing theory, slender body theory, subsonic compressible flow and Prandtl-Glauert rule, supersonic thin airfoil theory, introduction to performance, basic concepts of airfoil design. Prerequisite: graduate standing or permission of instructor.
Credit 3 units. EN: TU

E37 MEMS 5701 Aerospace Propulsion
Propeller, jet, ramjet and rocket propulsion. Topics include: fundamentals of propulsion systems, gas turbine engines, thermodynamics and compressible flow, one-dimensional gas dynamics, analysis of engine performance, air breathing propulsion system, the analysis and design of engine components, and the fundamentals of ramjet and rocket propulsion.
Credit 3 units. EN: TU

E37 MEMS 5703 Analysis of Rotary-Wing Systems
This course introduces the basic physical principles that govern the dynamics and aerodynamics of helicopters, fans and wind turbines. Simplified equations are developed to illustrate these principles, and the student is introduced to the fundamental analysis tools required for their solution. Topics include: harmonic balance, Floquet theory and perturbation methods.
Credit 3 units. EN: TU

E37 MEMS 5704 Aircraft Structures
Basic elements of the theory of elasticity; application to torsion of prismatic bars with open and closed thin-wall sections; the membrane analogy; the principle of virtual work applied to 2-D elasticity problems. Bending, shear and torsion of open and closed thin-wall section beams; principles of stressed skin construction, structural idealization for the stress analysis of wings, ribs and fuselage structures. Margin of safety of fastened connections and fittings. Stability of plates, thin-wall section columns and stiffened panels. Application of the finite element method for the analysis of fastened connections, structural fittings and problems of local stability of aircraft structural components.
Credit 3 units.

E37 MEMS 5705 Wind Energy Systems
A comprehensive introduction to wind energy systems, a practical means of extracting green and sustainable energy. Topics include: a historical perspective of wind turbines; horizontal axis and vertical axis wind turbines; the basic parameters such as power rating and efficiency; the structural components ranging from blade and hub to nacelle and tower; wind turbine aerodynamics, aeroelasticity and control systems; blade fatigue; statistical wind modeling; unsteady airfoil aerodynamics and downstream wake; and environmental considerations such as noise and aesthetics. Prerequisite: senior or graduate standing in engineering or permission of the instructor.
Credit 3 units. EN: TU

E37 MEMS 5801 Micro-Electro-Mechanical Systems I
Introduction to MEMS: Microelectromechanical systems (MEMS) are ubiquitous in chemical, biomedical and industrial (e.g., automotive, aerospace, printing) applications. This course covers important topics in MEMS design, micro-/nanofabrication, and their implementation in real-world devices. The course includes discussion of fabrication and measurement technologies (e.g., physical/chemical deposition, lithography, wet/dry etching, and packaging), as well as application of MEMS theory to design/fabrication of devices in a cleanroom. Lectures cover specific processes and how those processes enable the structures needed for accelerometers, gyros, FR filters, digital mirrors, microfluidics, micro total-analysis systems, biomedical implants, etc. The laboratory component allows students to investigate those processes first-hand by fabricating simple MEMS devices.
Credit 3 units. EN: TU

E37 MEMS 5802 Micro-Electro-Mechanical Systems II
A second course in MEMS. Topics include: physical microsystems; pressure sensors; accelerometers; microfluids and micro-scale thermal phenomena; electro-osmotic flows; microvalves; micropumps; optical MEMS; active flow control; system and constraints on microsystem design; compliant mechanisms; microfabricated electrochemical sensors; bio-MEMS; and case studies. Prerequisite: MEMS 5801 or permission of instructor.
Credit 3 units. EN: TU

E37 MEMS 5804 Engineering Project Management
Basic fundamentals and advanced concepts of engineering project management applicable to projects and programs, both large and small. Project management skills, techniques, systems, software and application of management science principles are covered and related to research, engineering, architectural and construction projects from initial evaluations through approval, design, procurement, construction and startup.
Credit 3 units. EN: TU

E37 MEMS 5912 Biomechanics Journal Club
This journal club is intended for graduate students and advanced undergraduates with an interest in biomechanics. We review landmark and recent publications in areas such as brain, cardiovascular and orthopedic biomechanics, discussing both experimental and modeling approaches. This course meets once weekly at a time to be arranged.
Credit 1 unit. EN: TU

E37 MEMS 598 Energy Design Project
Credit variable, maximum 6 units.

E37 MEMS 599 Master's Research
Credit variable, maximum 6 units.

E37 MEMS 600 Doctoral Research
Credit variable, maximum 9 units.

E37 MEMS 883 Master's Continuing Student Status

E37 MEMS 884 Doctoral Continuing Student Status

E37 MEMS 885 Master's Nonresident

E37 MEMS 886 Doctoral Nonresident

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Materials Science & Engineering (MS, DSc (p. 58), PhD (p. 54))

Mechanical Engineering (MEng, MS, DSc, PhD) (p. 58)

Project Management (Master, Certificate) (p. 70)

Robotics (MEng) (p. 34)

System Integration (Master, Certificate) (p. 70)

Systems Science & Mathematics (MS, DSc, PhD) (p. 34)

Administration

Dean's Office
314-935-6350

Department of Biomedical Engineering
314-935-6164

Department of Computer Science & Engineering
314-935-6160

Department of Electrical & Systems Engineering
314-935-5565

Department of Energy, Environmental & Chemical Engineering
314-935-5548

Department of Mechanical Engineering & Materials Science
314-935-6047

Engineering Information Technology
314-935-5097

Engineering Student Services
314-935-6100

Graduate Studies - Sever Institute

314-935-5484

Admission Procedures

Washington University in St. Louis encourages and gives full consideration to all applicants for admission and financial aid, without regard to race, color, age, religion, sex, sexual orientation, national origin, veteran status, or handicap. University policies and programs are nondiscriminatory.

A student must be admitted to a degree program in Engineering to earn a graduate degree, and the student must be admitted at least one semester prior to his or her anticipated graduation semester. Applications for admission to graduate standing should be filed with Engineering well in advance of the student's intended date for registering as a graduate-degree candidate. In addition to the application, a student should submit all required supporting documents.

To receive full admission, an applicant who has had no previous graduate work must have:

1. a bachelor's degree in an accredited curriculum in engineering, science or mathematics
2. earned at least a B average during the last two years of undergraduate work
3. the recommendation of the department or program to which the applicant is applying

The department or program recommendation will be based on the applicant's potential for success in the proposed course of study. To reach this judgment, the department or program will consider the applicant's undergraduate record, recommendations from former instructors, and if feasible, a personal interview.

All applicants for admission as full-time master's students are strongly encouraged to submit Graduate Record Examination (GRE) General Test scores (verbal, quantitative and written analytical). All applicants to doctoral programs are required to submit these scores.

Students failing to meet all of the criteria for full admission (with the exception of international students not residents of the United States at the time of application) may be recommended by the department or program for provisional admission. Students admitted provisionally must demonstrate their ability to pursue graduate work successfully and obtain recommendation for full admission within two semesters. In order to gain full admission, students admitted provisionally must maintain at least a B average in their course work during their first two semesters.

Students Not Candidate for Degree (SNCD)

Students choosing to take a course without applying to a degree program must be admitted to Engineering as an SNCD. Course prerequisites must be met, and an individual enrolling in a graduate course must typically show proof of a bachelor's degree. A student who registers for courses as an SNCD and later applies for admission to a graduate program in Engineering will be allowed to count a maximum of nine (9) units taken as an SNCD toward a graduate program, regardless of how many courses were taken as an SNCD.

International Students

International students who apply for admission to graduate standing, in addition to the above requirements, must present evidence of financial responsibility and ability to communicate effectively in the English language.

To demonstrate financial responsibility, the student must have a bank or similar source send a statement certifying that sufficient funds are available for the first year of study. If the funds being certified are in a sponsor's name, then the sponsor must also provide a letter stating that the sponsor is willing to use these funds to support the first year of study.

To prove the ability to use English satisfactorily, the student must pass the Test of English as a Foreign Language (TOEFL) given in other countries by the Educational Testing Service or GRE (http://gre.org).

Academic Policies

To view policies for PhD students, please refer to the Academic Information (http://bulletin.wustl.edu/grad/gsas/phd/academic) section of this *Bulletin*.

Course Load

The normal load for full-time graduate students is 9-12 units per semester. The course selection and load must be worked out with and approved by the student's adviser. Graduate students with research and teaching-assistant duties will typically enroll for course loads commensurate with the requirements of these duties. The course load will be determined after consultation with the student's adviser and the person supervising the student's duties as a research or teaching assistant. Students otherwise employed full- or part-time, on- or off-campus, will determine a satisfactory reduced course load with their advisers. International students on student visas are required to maintain full-time enrollment status.

Registration

All graduate students in Engineering must register each fall and spring semester until all degree requirements are complete. Newly admitted students will receive information on creating a WUSTL key from the University Registrar. The WUSTL key is used to register for courses online via WebSTAC during open registration periods. All registrations require online approval by the student's faculty adviser. Students may register in one of three categories:

- **Active Status:** A graduate student is viewed as having an active full-time status if enrolled in nine (9) or more units or an active part-time status if enrolled in fewer than nine (9) units. Graduate students must be authorized by their adviser prior to registration. International master's students on F1 and J1 visas are required to take a minimum of 9 units per semester except in their final semester. In order to have part-time status in their final semester, international master's students must complete a Reduced Course Load form available from the Office of International Students and Scholars (OISS).
- **Continuing Student Status:** The Continuing Student Status course option may be used when graduate students are approved to register for fewer than 9 units but still need to maintain their full-time status. When students are registered for the Master's Continuing Student Status (883) course or the Doctoral Continuing Student Status (884) course, they will still be viewed as having a full-time status, even if they are taking fewer than 9 units. Both placeholder courses are 0-unit audit courses with no tuition charges associated with them for engineering students; however, students may be charged health insurance and/or student activity fees associated with full-time status. The Txx or Exx 883 and Exx 884 course options are contingent upon adviser and departmental approval. **Note**: The 883 status is not available for master's students on F1 and J1 visas; domestic master's students may register under the 883 status only in their final semester with departmental approval. The 884 course is for DSc students only. Engineering PhD students will register for the LGS 9000 Full-Time Graduate Research/Study placeholder course to maintain full-time status.
- **Nonresident or Inactive Status:** Graduate students who do not need to maintain full-time status and who do not need to register for any course or research units during a given semester should, with departmental and adviser approval, register under the Nonresident/Inactive Status placeholder course option. Graduate students on an official leave of absence should also register under this status, but, again, only with adviser and departmental approval. (*Note*: PhD students in this situation must use Leave of Absence forms or other forms provided by the Graduate School). A DSc student wishing to register under a nonresident/inactive status should register using the Exx 886 course number. A master's student should register for the nonresident/inactive status using the Txx or Exx 885 course number. Both placeholder courses are 0-unit audit courses with no tuition charges associated with them for engineering students. Students registered this way are not viewed as full-time and will not automatically have university health insurance fees or coverage. This registration does not defer student loans, and it does not serve as a legal status for international students. The nonresident/inactive status will assure that the student's major program will remain open. This option is not available to international students (due to F1 and J1 visa requirements), unless approved by the Office for International Students and Scholars. A nonresident/inactive status is allowed only for a few semesters, at the department's discretion. Any student contemplating a nonresident/inactive status must remember to be aware of the residency requirements and the total time limitation required for degree completion.

Graduate Student Reinstatement: Graduate students who do not register in one of the above categories will have to apply for reinstatement if they wish to re-enroll at a future time. For reinstatement information, master's and DSc students should contact Engineering Student Services at 314-935-6100, and PhD students should contact the Graduate School at 314-935-6880. Students seeking reinstatement may be required to pay a reinstatement fee, take special reinstatement examinations, and repeat previous work if it fails to meet contemporary standards. Candidates for the DSc degree who apply for reinstatement may be required to repeat qualifying examinations.

Grades

Satisfactory academic progress is a prerequisite for continuation in engineering degree programs. Most financial awards, and all federally funded awards, are contingent upon the maintenance of satisfactory academic progress. The following are minimal standards of satisfactory academic progress for Doctor of Science and master's students. Degree programs may set stricter standards, but may not relax the standards listed below. Acceptability of grades below B- for fulfillment of degree requirements is determined by individual departments.

Doctor of Science (DSc) students must maintain a cumulative grade point average of at least 3.00.

- Academic probation occurs if a semester or cumulative grade point average drops below 3.00.
- A DSc student is eligible for academic suspension if any one of the follow occurs. The student:
  - receives an F grade in a course, or
  - earns a semester or cumulative grade point average less than 2.00, or
  - has been on probation for two semesters and has not attained a 3.00 cumulative grade point average.

Master's students must maintain a cumulative grade point average of at least 2.70.

- Academic probation occurs if a semester or cumulative grade point average drops below 2.70.
- A master's student is eligible for academic suspension if any one of the follow occurs. The student:
  - receives an F grade in a course, or
  - earns a semester or cumulative grade point average less than 2.00, or

- has been on probation for two semesters and has not attained a 2.70 cumulative grade point average.

Master's and DSc students eligible for academic suspension will have their names sent to their respective departments for their comments and recommendation before they are automatically suspended from a graduate program within the school. Students suspended may petition the associate dean in Engineering Student Services for reinstatement. Reinstatement petitions will be referred to the Graduate Board for review.

A grade of "I" in a course other than research must be removed no later than the close of the next semester; if not, the "I" turns into an "F" at the end of the next regular semester after the "I" grade was assigned.

Satisfactory academic progress for engineering students in PhD programs is monitored by the Graduate School as well as the degree program. Please refer to the Graduate School website (http://graduateschool.wustl.edu) for specific information related to policies concerning PhD students.

Transfer Credit

A maximum of 6 units of graduate credit obtained at institutions other than Washington University may be applied toward the master's degree. Approved transfer credit for undergraduate course work completed at a different institution cannot be posted until a letter is received from that institution's registrar, which states the graduate level course work was not used to satisfy undergraduate degree requirements.

A maximum of 24 units of graduate credit earned at institutions other than Washington University may be applied toward the Doctor of Philosophy degree and a maximum of 48 units for the Doctor of Science degree. Transfer credit must be recommended by the adviser, department or program chairman, and be approved by the appropriate registrar. No graduate courses carrying grades lower than B can be accepted for transfer toward any graduate degree.

No courses will be accepted toward degree requirements if the course exceeds the 10-year maximum time period unless they have formal approval of the Engineering Graduate Board.

Financial Information

Scholarships & Assistantships

Financial aid in the form of scholarships and assistantships is administered by the academic department or program that is the indicated major of the student. Scholarships, wages and stipends are only available to full-time students who can demonstrate the potential of making significant contributions to the department and its research activities. Continuation of scholarships and assistantships is based on academic performance.

Highly qualified applicants for full-time study will be considered for scholarships and assistantships based upon funds available in each department or program. Scholarships and assistantships are limited to available funds including government and private-sector grants and contracts. Graduate Record Examination (GRE) test scores must be provided by applicants to be considered for scholarships or assistantships. All fall semester doctoral applications will be reviewed for full financial assistantship if they are submitted by the application deadline of January 15.

Students holding scholarships and assistantships are required to devote full time to their graduate studies. They are not permitted to engage in any other work without special permission of Engineering. Awards may be made for the academic year (typically nine months) or the full calendar year (12 months), depending on the student's circumstances and the nature and source of the award.

Loans

The federal government provides a number of student loan programs with rules and requirements for each program. These are subject to change by the government agency overseeing the program and require that detailed financial information be provided by the student.

Interdisciplinary Opportunities

Washington University offers courses through Interdisciplinary Programs that include studies in a variety of disciplines that cross traditional academic boundaries and support academic areas outside the schools.

- A limited opportunity for some Washington University students to enroll in courses at Saint Louis University and the University of Missouri-St. Louis is available through the Inter-University Exchange Program (p. 74).
- The Skandalaris Center (p. 75) offers co-curricular programming and practical, hands-on training and funding opportunities to students and faculty in all disciplines and schools.

Inter-University Exchange Program

The Inter-University Exchange program between Washington University, Saint Louis University and the University of Missouri-St. Louis began in 1976 as an exchange agreement encouraging greater inter-institutional cooperation at the graduate level. Over time, this program has evolved to include undergraduate education, however, the basic provisions of the original agreement are still in place today and participation continues to be at the discretion of each academic department or unit.

At Washington University, there are several schools that **do not participate** in this program (i.e., degree-seeking students in these schools are not eligible to participate in the IE program and courses offered in these schools are not open to SLU and UMSL students attending Washington University through the IE program). They are the School of Law, the School of Medicine, University College and the Summer School. The Washington University schools that are open to participation in the Inter-University Exchange program may have specific limitations or requirements on participation; details are available in those offices.

The following provisions apply to all course work taken by Washington University students attending Saint Louis University or the University of Missouri-St. Louis through the Inter-University Exchange program:

- Such courses can be used in the fulfillment of degree or major requirements. (Students should consult with their dean's office for information about how IE course work will count toward GPA, units, and major requirements.)
- Such courses are not regularly offered at Washington University.
- Registration for such courses requires preliminary approval of the student's major/department adviser, the student's division office or dean, and the academic department of the host university.
- Students at the host institution have first claim on course enrollment (i.e., a desired course at SLU or UMSL may be fully subscribed and unable to accept Washington University students).
- Academic credit earned in such courses will be considered as resident credit, not transfer credit.
- Tuition for such courses will be paid to Washington University at the prevailing Washington University rates; there is no additional tuition cost to the student who enrolls in IE course work on another campus. However, students are responsible for any/all fees charged by the host school.
- Library privileges attendant on enrolling in a course on a host campus will be made available in the manner prescribed by the host campus.

Instructions

Washington University students must be enrolled full-time in order to participate in the IE program and have no holds, financial or otherwise, on their academic record at Washington University or at the host institution.

1. The student must complete the Inter-University Exchange application form. Forms are available from the Office of the University Registrar and on its website (link below).
2. The student must provide all information requested in the top portion of the form and indicate the course in which they wish to enroll.
3. The student must obtain the approval signature of the professor teaching the class (or department chair) at SLU or UMSL, preferably in person.
4. The student also must obtain approval signatures of his or her major adviser at Washington University and the appropriate individual in his or her dean's office.
5. Completed forms must be submitted to the Office of the University Registrar in the Women's Building a minimum of one week before the start of the term.

Course enrollment is handled administratively by the registrars of the home and host institutions. Washington University students registered for IE course work will see these courses on their class schedule and academic record at WebSTAC under departments I97 (SLU) and I98 (UMSL). Final grades are recorded when received from the host institution. The student does not need to obtain an official transcript from SLU or UMSL to receive academic credit for IE course work at Washington University.

Contact:	Office of the University Registrar
Phone:	314-935-5959
Email:	registrar@wustl.edu
Website:	http://registrar.wustl.edu/student-records/registration/the-inter-university-exchange-program

Skandalaris Center for Interdisciplinary Innovation and Entrepreneurship

Mission

The Skandalaris Center for Interdisciplinary Innovation and Entrepreneurship (http://skandalaris.wustl.edu) has a threefold mission:

1. Attract the maximum possible number of students, faculty and alumni from all disciplines into the interdisciplinary innovation and entrepreneurship funnel.
2. Provide high quality, venture-specific, practical entrepreneurial training to all.
3. Provide access to early stage seed capital to the most promising Washington University entrepreneurs and innovations.

This mission is accomplished through a four-part pipeline: **Touch**, **Engage**, **Train** and **Launch**.

Events & Workshops

Most events and workshops (http://skandalaris.wustl.edu/training/workshops) are open to all graduate students in all disciplines, including the Evidence-Based Entrepreneurship Series, the Washington University Startup Training Lab, and the Boeing Patent Challenge (http://skandalaris.wustl.edu/boeing-challenge).

Programs

There are two graduate-only programs that provide exceptional engagement and entrepreneurial training:

1. **InSITE Fellowship** (http://skandalaris.wustl.edu/training/insite-fellowship): a prestigious, extracurricular fellowship that connects graduate students to the St. Louis entrepreneurial community as well as to an extensive, international network of entrepreneurs, venture capitalists, innovators and leaders
2. **PhD Citation in Entrepreneurship** (http://skandalaris.wustl.edu/training/recognition-in-entrepreneurship/entrepreneurship-citation) and the **Master's Declaration of Accomplishment in Entrepreneurship** (http://skandalaris.wustl.edu/training/recognition-in-entrepreneurship/declaration-of-accomplishment-in-innovation-and-entrepreneurship): opportunities to be recognized for outstanding achievements in entrepreneurship throughout the graduate school career

Courses

There are various entrepreneurial courses offered through each school at Washington University. Two such courses include Business Planning for New Enterprises [The Hatchery] (MGT 524) through Olin School of Business and Social Entrepreneurship (S50 SWSA 5060) through the top-ranked Brown School at Washington University.

Student Groups

IDEA Labs (http://ideas.wustl.edu), The BALSA Group (http://www.thebalsagroup.org), and The Entrepreneurship and Venture Capital Association (http://olinwustl.campusgroups.com/evca/about) provide additional opportunities to train and even launch a venture.

Competitions

Competitions such as the Skandalaris Center Cup (commercial ventures), the Social Enterprise and Innovation Competition (social ventures), and the Global Impact Award (hybrid companies) allow participants to receive intensive training and access to funding.

Please contact (https://skandalaris.wustl.edu/contact-us) the Skandalaris Center for additional information about all programs.

Contact:	Jessica Stanko
Phone:	314-935-9134
Email:	sc@wustl.edu
Website:	http://skandalaris.wustl.edu

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