WPI

Graduate Catalog

2017-2018

Academic Calendar 2017–2018

The graduate academic calendar is divided into fall, spring and summer semesters. The undergraduate academic calendar is divided into seven-week terms: the fall semester terms, A and B; the spring semester terms, C and D. Term E is the summer semester. Some graduate courses are offered on a term-basis, coincidental with the undergraduate calendar. Details of the WPI academic calendar, including dates on which graduate classes begin and end for each semester, appear below.

Fall 2017

August 18-19
New Teaching Assistant Training

August 22
New Graduate Student Orientation

August 24
First Day of Graduate Classes
(Follow Monday Schedule)

September 4
Labor Day Holiday (No Classes)

September 7
Deadline for submission of Electronic Theses and Dissertations

October 1
Deadline for filing application for February Graduation

October 13-23
Semester Break (No Classes)

October 24
Graduate Classes Resume

November 22-26
Thanksgiving Break (No Classes)

December 15
Last Day of Graduate Classes, Fall Semester

Spring 2018

January 8
New Graduate Student Orientation

January 9-10
New Teaching Assistant Training

January 10
First Day of Graduate Classes
(Follow Monday Schedule)

January 15
Martin Luther King Day (No Classes)

January 24
Deadline for submission of Electronic Theses and Dissertations

February 1
Deadline for filing application for May Graduation

February 7
Graduate Research Innovation Exchange Poster Celebration (GRIE)

March 3-11
Semester Break (No Classes)

March 12
Graduate classes resume

April 16
Patriot's Day (No Classes)

April 24
GRIE Poster Final Competition

April 24
i3: Investing in Ideas with Impact

April 26
Deadline for submission of Electronic Theses and Dissertations for May 2018 Candidates

May 1
Last Day of Graduate Classes
(Follow Friday Schedule)

May 10
Graduate Commencement 2018

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Graduate Programs

Aerospace Engineering
Master of Science in Aerospace Engineering
Ph.D. in Aerospace Engineering

Bioinformatics and Computational Biology
Master of Science in Bioinformatics and Computational Biology
Ph.D. in Bioinformatics and Computational Biology

Biology and Biotechnology*
Master of Science in Biology/ Biotechnology
Master of Science in Biotechnology
Ph.D. in Biology and Biotechnology

Biomedical Engineering*
Master of Engineering in Biomedical Engineering
Master of Science in Biomedical Engineering
Ph.D. in Biomedical Engineering

Business
Graduate Certificate
Master of Business Administration (M.B.A.)
Master of Science in Information Technology
Master of Science in Management
Master of Science in Marketing and Innovation
Master of Science in Operations Analytics and Management
Master of Science in Supply Chain Management
Ph.D. in Business Administration

Chemical Engineering
Master of Science in Chemical Engineering
Professional Master of Science in Chemical Engineering
Ph.D. in Chemical Engineering

Chemistry and Biochemistry
Master of Science in Biochemistry
Master of Science in Chemistry
Ph.D. in Biochemistry
Ph.D. in Chemistry

Civil and Environmental Engineering
Graduate Certificate
Master of Engineering in Civil Engineering
Master of Science in Civil Engineering
Master of Science in Environmental Engineering
Interdisciplinary Master of Science in Construction Project Management
Advanced Certificate
Ph.D. in Civil Engineering

Computer Science
Graduate Certificate
Master of Science in Computer Science
Master of Science in Computer Science specializing in Computer Security
Advanced Certificate
Ph.D. in Computer Science

Data Science
Graduate Certificate
Master of Science in Data Science
Ph.D. in Data Science

Electrical and Computer Engineering
Graduate Certificate
Master of Engineering in Electrical and Computer Engineering
Master of Engineering in Power Systems Engineering
Master of Science in Electrical and Computer Engineering
Advanced Certificate
Ph.D. in Electrical and Computer Engineering

Fire Protection Engineering
Graduate Certificate
Master of Science in Fire Protection Engineering
Advanced Certificate
Ph.D. in Fire Protection Engineering

Interactive Media & Game Development
Master of Science in Interactive Media & Game Development

Interdisciplinary Programs
Graduate Certificate in Nuclear Science and Engineering
Master of Science in:
– Power Systems Management
– Systems Modeling
Ph.D. in Interdisciplinary Studies

Learning Sciences and Technologies
Master of Science in Learning Sciences and Technologies
Ph.D. in Learning Sciences and Technologies

Manufacturing Engineering
Graduate Certificate
Master of Science in Manufacturing Engineering
Ph.D. in Manufacturing Engineering

Materials Process Engineering
Master of Science in Materials Process Engineering

Materials Science and Engineering
Master of Science in Materials Science and Engineering
Ph.D. in Materials Science and Engineering

Mathematical Sciences
Master of Mathematics for Educators
Professional Master of Science in Financial Mathematics
Professional Master of Science in Industrial Mathematics
Master of Science in Applied Mathematics
Master of Science in Applied Statistics
Ph.D. in Mathematical Sciences

Mechanical Engineering
Graduate Certificate in Mechanical Engineering for Technical Leaders
Master of Science in Mechanical Engineering
Ph.D. in Mechanical Engineering

Physics
Master of Science in Physics
Ph.D. in Physics

Robotics Engineering
Graduate Certificate
Master of Science in Robotics Engineering
Ph.D. in Robotics Engineering

STEM for Educators
Master of Science in Mathematics for Educators (MMED)
Master of Science in Physics for Educators (MPED)

Social Science and Policy Studies
Graduate Certificate in System Dynamics
Master of Science in System Dynamics
Master of Science in System Dynamics and Innovation Management
Interdisciplinary Ph.D. in Social Science and Policy Studies

Systems Engineering
Graduate Certificate
Advanced Certificate
Master of Science in Systems Engineering
Ph.D. in Systems Engineering

*Fall Semester admission only

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Graduate Programs by Degree

WPI offers graduate study leading to the master of science, master of engineering, master of mathematics for educators, master of business administration, and the doctor of philosophy degrees.

The schedule of courses over a period of time generally allows a student taking three or four courses per semester to complete the course requirements for most Master's degree programs in about two years. Students taking two courses per semester complete the course requirements for the master of science or engineering degrees in about three years, or the master of business administration degree in about four years.

Doctor of Philosophy (Ph.D.) Degrees*

Available in the following programs:

- Aerospace Engineering
- Biochemistry
- Bioinformatics and Computational Biology
- Biology and Biotechnology
- Biomedical Engineering
- Business Administration
- Chemical Engineering
- Chemistry
- Civil Engineering
- Computer Science
- Data Science
- Electrical and Computer Engineering
- Fire Protection Engineering
- Interdisciplinary Studies
- Learning Sciences and Technologies
- Manufacturing Engineering
- Materials Science and Engineering
- Mathematical Sciences
- Mechanical Engineering
- Physics
- Robotics Engineering
- Social Science and Policy Studies
- Systems Engineering

**available only on a full-time basis*

Master of Science (M.S.) Degrees

Available, on a full-time and part-time basis, in the following programs:

- Aerospace Engineering
- Applied Mathematics
- Applied Statistics
- Biochemistry*
- Bioinformatics and Computational Biology
- Biology/Biotechnology*
- Biomedical Engineering
- Biotechnology
- Chemical Engineering*
- Chemistry*
- Civil Engineering
- Computer Science
  - Specializing in Computer Security
- Construction Project Management
- Data Science
- Electrical and Computer Engineering
- Environmental Engineering
- Financial Mathematics
- Fire Protection Engineering
- Industrial Mathematics
- Information Technology
- Interactive Media & Game Development
- Interdisciplinary Studies
  - Power Systems Management
  - Systems Modeling
- Learning Sciences and Technologies
- Management
- Marketing and Innovation
- Manufacturing Engineering
- Materials Process Engineering
- Materials Science and Engineering
- Mechanical Engineering
- Operation Analytics and Management
- Physics
- Robotics Engineering
- Supply Chain Management
- System Dynamics
- System Dynamics and Innovation Management
- Systems Engineering

**available only on a full-time basis*

Master of Engineering (M.E.) Degrees

Available in the following programs:

- Biomedical Engineering
- Civil Engineering
  - Environmental Engineering
  - Master Builder Program
- Electrical and Computer Engineering
- Power Systems Engineering

Master of Business Administration (M.B.A.) Degree

Provides students with strategies for the successful application of technology to complex business environments. The degree requirements are described in this catalog and in a separate brochure available from the Robert A. Foisie School of Business at 508-831-4665, or on the web at http://business.wpi.edu.

Master of Mathematics for Educators (MME) Degree

WPI offers a Master in Mathematics for Educators, a part-time program for teachers of mathematics at the middle school, secondary, and community college levels. Students in this program may earn a content-based degree afternoons and evenings while still teaching full time. Taught by professors of mathematics at WPI, the program is designed to permit the teachers to learn from professors' research interests and includes an understanding of current developments in the field. Scholarship aid, which covers approximately 40% of the cost of tuition, is available to qualified participants. The MME degree may be used to satisfy the Massachusetts Professional License requirements, provided the person holds an Initial License.

Master of Science in Mathematics for Educators (MMED) Program

Designed especially for middle school, high school and community college educators, the Master of Science in Mathematics for Educators is a part-time, afternoon and evening program of study that puts emphasis on math

content courses while also incorporating core assessment and evaluation theory coursework and a culminating project designed by the participant. Participants are additionally able to keep up-to-date on the latest research by working with professors in the field. The MMED may satisfy Massachusetts requirements to move from an Initial License to a Professional License.

Master of Science in Physics for Educators (MPED) Program

Designed especially for middle school, high school and community college educators, the Master of Science in Physics for Educators is a part-time, afternoon and evening program of study that puts emphasis on physics content courses while also incorporating core assessment and evaluation theory coursework and a culminating project designed by the participant. Participants are additionally able to keep up-to-date on the latest research by working with professors in the field. The MPED may satisfy Massachusetts requirements to move from an Initial License to a Professional License.

Combined Bachelor/Master's Program

Introduction

WPI undergraduates can begin work on a graduate degree by enrolling in a combined Bachelor's/Master's program. This accelerated course of study allows students to obtain an M.S. degree after only five years of full-time work (i.e., typically one year after completion of the B.S.). Students often obtain the B.S. and M.S. in the same field or department, but with careful planning some students complete the combined B.S./M.S. program in two different fields. Students are encouraged to review the various options available for pursuing the combined B.S./M.S. program within a specific department or program by visiting the relevant section within the Graduate Catalog. (Throughout this section, "M.S." will be used to refer to all Master's-level degrees; most students who complete the combined program obtain the M.S.).

Planning Your Program

Because B.S./M.S. students use some approved courses to satisfy the requirements of both degrees simultaneously, it is crucial for them to plan their curriculum early in their undergraduate career.

The specific course and MQP requirements for a B.S./M.S. program are determined individually, so students should consult with their own advisor as well as the graduate coordinator in the department in which they plan to pursue their M.S. degree early in their Junior year. This consultation, or series of consultations, should produce a slate of approved undergraduate courses that will be used for graduate credit. Sometimes the instructors of these courses will ask B.S./M.S. students to complete additional work, or will otherwise hold them to higher standards of achievement.

A student's advisor and graduate coordinator will also determine what role the MQP will play in the B.S./M.S. program. Sometimes the MQP provides a foundation for a thesis. In cases where the B.S. and M.S. are not awarded in the same field, the MQP usually relates to the graduate program's discipline.

Once the specific course and MQP requirements have been established, students complete a Course Selection Form which is submitted to the relevant department(s) for approval. This written agreement constitutes the set of conditions that must be met for a student to complete the B.S./M.S. program. They are a plan for completing the requirements for both degrees and they will not supersede or otherwise obviate departmental and university-wide requirements for either degree. The completed, signed form must be submitted to the Registrar before the student may matriculate in the combined program.

How to Apply

Students almost always apply for admission to the B.S./M.S. program in their Junior year, typically after they have established their curriculum and other program requirements and completed the Course Selection Form with their faculty advisors. Applications are submitted to the Office of Graduate Admissions and are processed with all other graduate applications. Once a decision has been reached, the Office of Graduate Admissions will notify the student, usually within six weeks of receiving the application.

Program Requirements

Only registered WPI undergraduates may apply for admission to the combined B.S./M.S. programs. Students are considered undergraduates, no matter what courses they have completed, until they have met all of the requirements for the Bachelor's degree. In order to receive the B.S. and the M.S., all of the requirements for both degrees must be completed.

In most departments a student may take up to four years to complete the Master's portion of the B.S./M.S. program. There are exceptions, however, so students are advised to discuss their timetable with the appropriate advisor or graduate coordinator. Students who stop registering for classes for an extended length of time may be asked to petition the Committee for Graduate Studies and Research (CGSR) to continue their program.

Credit Equivalence and Distribution

No more than 40% of the credit hours required for the Master's degree, and which otherwise meet the requirements for each degree, may be used to satisfy the requirements for both degrees. In some departments, students may not double-count more than 30% of their graduate credits. Consult the department entries in the graduate catalog for the requirements of your program.

Double-counted courses are recorded on the transcript using the credit hours/units and grades appropriate at the graduate or undergraduate levels. For students in the combined B.S./M.S. program, approved undergraduate courses are assigned graduate credit with a conversion rate of 1/3 WPI undergraduate unit = 2 graduate credit hours, while graduate courses applied toward the undergraduate degree are awarded undergraduate units with a conversion rate of 1 graduate credit hour = 1/6 undergraduate unit.

Interdisciplinary Master's and Doctoral Programs

WPI encourages interdisciplinary research. Students interested in such options should do so with the assistance of WPI faculty, as these programs require internal sponsorship (see Interdisciplinary Programs pages 4 and 110).

Graduate and Advanced Graduate Certificates

Keeping pace with technological advancement today is a never-ending task. WPI's innovative graduate certificate programs help technical and business professionals keep up to date with advances in technologies and business practices without a commitment to a graduate degree program. WPI offers two certificate programs: the Graduate Certificate (GC) and the Advanced Certificate (AC).

Graduate Certificate Program

The Graduate Certificate (GC) provides opportunities for students holding undergraduate degrees to continue their study in an advanced area. A bachelor's degree is the general prerequisite; however, some departments also look for related background when making admission decisions. GC students are required to complete four to six courses totaling 12 to 18 credit hours in their area of interest. GC courses can be applied to a WPI graduate degree if the student is subsequently admitted to a degree program in the same discipline.

Graduate certificates are offered in the following programs:

- Business
- Civil and Environmental Engineering
- Computer Science
- Data Science
- Electrical and Computer Engineering
- Fire Protection Engineering
- Manufacturing Engineering
- Mechanical Engineering for Technical Leaders
- Nuclear Science and Engineering
- Power Systems Engineering
- Power Systems Management
- Robotics Engineering
- Supply Chain Management
- System Dynamics
- Systems Engineering
- Systems Thinking

Additional programs may be developed in consultation with an academic adviser. For the most current listings go to https://www.wpi.edu/academics/study

Advanced Certificate Program

The Advanced Certificate (AC) provides master's degree holders with an opportunity to continue their studies in advanced topics in the discipline in which they hold their graduate degrees or that is closely related to their graduate fields. The AC includes four to six courses totaling 12 to 18 credits, none of which were included in the student's prior master's program or in any other certificate program.

Each participating department identifies one or more guideline programs; however, each student's program of study may be customized with the academic advisor's approval to satisfy the student's unique interests.

Advanced Certificates are offered in the following programs:

- Civil and Environmental Engineering
- Computer Science
- Electrical and Computer Engineering
- Fire Protection Engineering
- Systems Engineering

Additional specializations may be developed in consultation with an academic advisor.

Application Process

Application to the GC and AC requires submission of an official application form, official transcripts of all college-level work, and a $70 application fee (waived for WPI alumni) to the Office of Graduate Admissions. Individual departments may require additional information. International students may apply to certificate programs. However, for WPI to issue the I-20 form for a student visa, international students must be registered for a minimum of nine credits on campus during their first semester and must complete their program within one year. Students apply online at http://grad.wpi.edu/+apply.

Admission and Matriculation

Admission to a certificate program is granted by the faculty of the sponsoring department through the Graduate Admissions Office. A student accepted into a master's or doctoral program may apply to a certificate program only after the graduate committee of the degree (M.S. or Ph.D.) granting program or department approves, and as long as all of the following conditions are met:

1) Admitted master's or doctoral program students may be awarded one certificate for which course credits are used to satisfy requirements for both the graduate degree (M.S. or Ph.D.) and the Graduate Certificate or advanced graduate certificate.
2) Graduate course credits used to satisfy the graduate certificate or advanced graduate certificate and graduate degree (M.S. or Ph.D.) requirements cannot also be counted toward a third credential, such as a Graduate Certificate, Advanced Graduate Certificate, graduate or undergraduate degree.
3) No more than one-third of course credit applied to a Graduate Certificate or advanced Graduate Certificate or graduate degree can be earned by transfer credit.

A Graduate or Advanced Certificate will not be awarded without admission into a certificate program.

Registration Procedures

GC and AC students register at the same time as other WPI graduate students, follow the same registration procedures, and participate in the same classes.

Tuition and Fees

Tuition and fees for GC and AC students are the same as for all other WPI graduate students.

Plan of Study

Following admission, certificate students will be assigned an academic advisor. Within the first three months of admission, certificate students are required to obtain approval for their Plan of Study from their faculty advisor. The student, the academic advisor and the department will maintain copies of the Plan of Study. Students may initiate written requests to the advisor to modify the program. The student, the academic advisor and the department must retain copies of any approved program modification(s).

Academic Policies

Academic policies regarding acceptable grade point averages for certificate students follow the same guidelines as those established for degree-seeking graduate students with the following exception: If a GC or AC student's grade point average falls below 2.5 after completing nine credits, he/she will be withdrawn from the program unless the academic department intervenes.

Program Completion

Satisfactory completion of a GC or AC requires a cumulative grade point average of 3.00 or better (A = 4.0) with individual course grades of C or better. Upon satisfactory completion of the program, students will receive a certificate of Graduate Study or a Certificate of Advanced Graduate Study in the chosen discipline. Students are responsible for submitting the signed, completed Plan of Study to the Registrar's Office to receive the certificate.

Transferring from a Certificate Program to a Graduate Degree Program

Admission to a certificate program is not equivalent to admission to a degree program. However, many certificate students eventually choose to pursue a WPI degree program. Students enrolled in a certificate program who would like to pursue a master's or doctorate must meet the application and admission requirements for the specific degree program as described in the Graduate Catalog. All GC and AC course credits will apply to a WPI graduate degree provided that the student is admitted to a graduate degree program and the courses are acceptable to that degree program.

Earning a Second Certificate

A student admitted into a certificate program who wishes to work toward a second certificate program must apply to that second certificate program for admission. The application fee will be waived for the second application. Courses counted toward one certificate may not count toward any other certificate.

Corporate and Professional Education

WPI Corporate and Professional Education (CPE) brings expert, integrated, and practical instruction into leading organizations throughout the Northeast and beyond. We maximize the value of a company's investment in its employees through education that targets their unique business and industry needs.

Through collaboration with CPE, our partners experience a wealth of benefits:

- Employees who are educated to solve immediate and strategic problems specific to their company's highest needs
- Increased employee retention due to a demonstrated commitment to employee development
- Greater collaboration across company departments
- An effective recruiting tool for attracting new talent in a competitive market

Whatever the needs of an organization, WPI CPE has the solution: from focused, single-topic programs to those integrating multiple disciplines. We tailor and deliver first-class education to our partners, giving them a competitive edge in their unique market.

Corporate Graduate Programs

For decades WPI has collaborated with businesses to develop meaningful employee education that makes sense for their workforce. We offer a completely customizable experience, including on-site and online instruction options.

Our experienced staff develops and delivers programs designed to meet a specific company's needs:

- Single courses, graduate & undergraduate certificate programs, and full graduate degree programs
- A variety of disciplines: science, engineering, technology, and management
- Interdisciplinary tracks covering multiple topics
- Instruction from both technical and managerial perspectives

Whether delivered on-site or online, WPI's corporate programs are held to the university's high standards:

- Plans of study comply with applicable state and federal education-board requirements
- Concepts and materials are consistent with on-campus courses, and customized to each company
- All faculty are appointed by WPI academic department heads
- All faculty members are experts in their fields, and many are working on cutting-edge research in their disciplines

WPI Programs Available through CPE

Corporate and Professional Education extends WPI's campus and highly technical education to interested companies by facilitating onsite delivery of a number of WPI graduate programs.

The CPE office works closely with clients to design and deliver educational solutions to their workforces. Students in these programs earn the same degrees as their on-campus counterparts.

Businesses currently benefit from the following WPI programs, and others, at their locations:

- Electrical & Computer Engineering: Master of Science
- Mechanical Engineering: Master of Science
- Power Systems: Master of Science & Master of Engineering (MEng)
- Systems Engineering: Master of Science
- Master of Business Administration (MBA)

Other select on-campus programs from WPI are available for onsite corporate delivery.

Contact and Information:

For more information, please contact WPI Corporate and Professional Education online, by phone, or by email:

cpe@wpi.edu

+1-508-831-5517

https://www.wpi.edu/employers-partners/corporate-education

WPI Online

WPI Online programs are designed with the working professional in mind. No matter your location or schedule, an advanced degree from WPI is within reach.

For more than thirty years, we have delivered superior distance education to graduate students around the world. It is our mission to make sure each student feels connected, supported, and successful.

Our online students receive the same world-class instruction as our on-campus students, delivered by expert WPI faculty. Support services tailored to the needs of working professionals are also available, in addition to the resources offered to every WPI student.

Quality Graduate Education

Our convenient online courses are open to both on-campus and distance learners.

All courses and degrees delivered online contain the same content and material one would receive in a traditional classroom. In addition, online students have the benefit of 24/7 access to their courses.

Please note: online students are held to the same high standard as all WPI students. They are expected to keep pace with course content and engage actively in all of their courses, adding value to the collaborative learning environment.

This level of participation requires regular access to high-speed Internet via a personal computer.

Programs of Study

The following graduate-level programs are offered online. Please note that the entire degree can be completed online but not every course in the program may be available online.

Area of Study	Certificate	Master
Biotechnology		Master
Construction Project Management	Certificate	Master
Cyber Security	Certificate	
Data Science	Certificate	Master
Electrical and Computer Engineering	Certificate	Master
Environmental Engineering		Master
Fire Protection Engineering	Certificate	Master
Mechanical Engineering		Master
Mechanical Engineering for Technical Leaders	Certificate	
Nuclear Science & Engineering		
Power Systems Engineering	Certificate	Master
Power Systems Management	Certificate	Master
Robotics Engineering		Master
System Dynamics	Certificate	Master
Systems Engineering	Certificate	Master
Systems Thinking	Certificate	

*New programs become available online throughout the academic year. Please visit www.wpi.edu/+online for the most current online program offerings.

Student Services

Online students have unique questions, concerns, and needs. With WPI Online, you're never alone. You will benefit from the services our on-campus students receive, and then some, including:

- Online orientation
- Virtual library access
- Software & mobile support
- Career counseling & placement
- Tuition & financial aid help

Plus, a dedicated team provides our online students with individualized support every step of the way, from application to graduation.

Contact and Information:

WPI Online provides online graduate students with personalized assistance and acts as their liaison to all other university offices. Students can reach WPI Online via the website, by phone, and by email:

WPI Online

online@wpi.edu

+1-508-831-5517

www.wpi.edu/+online

WPI is registered with the Minnesota Office of Higher Education pursuant to Minnesota Statutes sections 136A.61 to 136A.71. Registration is not an endorsement of the institution. Credits earned at the institution may not transfer to all other institutions

Admission Information

Applying to WPI

Prospective graduate students submit their applications for all WPI graduate programs online at grad.wpi.edu/+apply.

Each department requires different credentials for admission. A table of each department's requirements can be found on page 13.

A completed undergraduate degree is a pre-requisite for beginning all graduate degree programs at WPI. All graduate students are expected to have completed their undergraduate degree at the time of matriculation.

WPI admission requirements include the following:

- A completed Application for Admission to Graduate Study.
- A non-refundable $70 application fee (waived for WPI alumni and matriculating WPI students).
- College transcripts in English and the original language from all accredited degree-granting institutions attended. Admitted students must provide official transcripts with an indication that the bachelor's degree has been awarded before they matriculate.
- Three letters of recommendation from individuals who can comment on the applicant's qualifications for pursuing graduate study in the chosen field. Applicants are required to invite their recommenders to submit letters through the online application only.
- Several programs require a statement of purpose (see page 13). This is a brief essay discussing background, interests, academic intent, and the reasons the applicant feels s/he would benefit from the program. The statement of purpose must be submitted electronically with the online application.
- The School of Business requires all applicants to submit a resume electronically with the online application.
- Proof of English language proficiency must be submitted by all applicants for whom English is not their first language. Applicants must submit an official score report from either the TOEFL (Test of English as a Foreign Language) or IELTS (International English Language Testing Service). WPI does not accept paper copies of these scores; only official scores sent electronically from the testing service will be accepted. The minimum scores for admission are:
  TOEFL: 84 (internet-based test)
  IELTS: 7.0 overall band score with no sub-score lower than 6.5

These are the minimum scores for admission to WPI. Some departments have higher minimums. Students being considered for a Teaching Assistant position will have a higher required minimum TOEFL. Please see the section on Financial Information/ Teaching Assistantships for more details.

Applicants who have completed two years of full-time study at a college or university in the U.S., the U.K., Ireland, Australia, New Zealand, or the Anglophone regions of Africa, Canada, or the Caribbean, within five years of matriculating at WPI are not required to submit TOEFL or IELTS scores.

WPI's institutional code for the TOEFL is 3969. Scores are valid for two years from the test date. For more information, or to take the TOEFL, go to: www.toefl.org. For more information on the IELTS, or to take the exam, go to: www.ielts.org.

- Some programs require the GRE (Graduate Record Examination). Consult the table on page 13 for program requirements. There is no WPI minimum GRE score for admission. WPI's institutional code for the GRE is 3969. Scores are valid for five years from the test date. For more information, or to take the GRE go to: www.ets.org/gre.

The Office of Graduate Admissions will retain incomplete applications and their associated credentials for one year after the application was started. If the application remains incomplete for one year, WPI reserves the right to cancel it and destroy all associated documents and credentials.

All applications and all support material become the property of WPI once they have been received by the Office of Graduate Admissions.

Three-Year Bologna-Process Degrees

WPI welcomes applications from students who have three-year Bologna-compliant undergraduate degrees from European universities. Applicants who hold these credentials will be evaluated for admission on a case-by-case basis.

Priority Dates

Students who want to apply for fall admission should submit their applications by the preceding January 1st and complete the dossier as soon as possible after that date.

Students who are seeking admission to the spring semester should submit their applications by the preceding October 1st and complete the dossier as soon as possible after that date.

Some departments have strict deadlines; others admit students year-round. Consult the WPI website for more details.

Funding is disbursed by the admissions committees in each of the academic departments. These decisions are made in tandem with the admissions decision, so there is no separate application for assistantships or fellowships.

Prospective students must indicate that they want to be considered for funding when they apply for admission. The application should be complete on or before January 1st to ensure consideration. Applications that are completed during the two weeks following January 1st will also receive the earliest consideration for funding.

With each passing month the availability of funds decreases, so applications should be completed, if possible, before the end of January.

Admission

Each department, program, or sponsoring group is responsible for making admissions decisions. Their decisions are communicated by the Office of Graduate Admissions. In general, offers of admission are good for one year.

Sometimes a department will recommend admission to a degree program that differs from the program specified in the student's application. Most typically, a department will admit a Ph.D. applicant to a Master's program. Students in such a position should contact the graduate coordinator in their program to find out what criteria they will have to meet to gain admission to the Ph.D. program in the future.

A current WPI graduate student who would like to complete a second graduate degree in another department must apply for admission to the second program. In general, standard application procedures are followed, but a copy of the first application and its supporting materials can sometimes be used as the basis for the second. No application fee is required. Students who wish to change from one degree program to another must complete a second graduate application.

Under some circumstances a student not yet admitted to a program may earn graduate credit towards the requirements for a graduate degree. But such students must keep in mind that permission to register does not constitute admission to a degree or certificate program, nor does it guarantee admission. It is also important to bear in mind that the number credits that can be applied to the degree is limited. Students are thus encouraged to apply for admission to a program at the earliest possible date.

Applicants who would like to be considered for more than one degree program must complete and submit a separate application form for each program.

M.S. to Ph.D.

In some programs, an M.S. student who want to continue to a Ph.D. in the same program can be admitted to the Ph.D. program without completing a new application. Instead the graduate coordinator or program chair will write a letter to the Dean of Graduate Studies to the effect that the student will have met the qualifications for admission to the Ph.D. once the M.S. has been completed. The letter will be copied to the Office of Graduate Admissions, the Registrar, and the graduate studies committee in the program.

Confirmation of Admission

Admission to a WPI graduate program is officially granted via a letter from the Office of Graduate Admissions. No other communication from the university (e.g., email from a department) confers admission on an applicant.

The official admission letter asks students to respond to their offer online on the Graduate Admission Response Form. Communication with the department or program directly does not officially confirm the intention to attend, and may not initiate the necessary steps for enrollment.

A non-refundable deposit of $500, which will be credited to tuition and fees, is required of students who plan to attend.

Deferred Enrollment

An admitted student who wishes to defer enrollment must make a request in writing to the Office of Graduate Admissions. Students typically receive a one-time deferral of up to twelve months. Funded students generally can not defer their funding. WPI requires a $500 non-refundable deposit for all deferrals. This deposit will be credited to the student's tuition upon arrival.

Application Requirements

Graduate Certificates

Applicants to all graduate certificate programs must submit the following credentials for the application to be complete.

1. Online application form
2. Transcripts from all colleges or universities attended, and official proof of a completed Bachelor's degree before matriculating.
3. Proof of English proficiency (for non-native English speakers)
4. $70 application fee

Individual departments may require additional information.

Master's and Doctoral Degrees

Applicants to all graduate degree programs must submit the following credentials for the application to be complete.

1. Online application form
2. Transcripts from all colleges or universities attended, and official proof of a completed Bachelor's degree before matriculating.
3. Three letters of recommendation, submitted online
4. Proof of English proficiency (for non-native English speakers)
5. Exams and essays as noted below
6. $70 application fee

Department/Program	GRE	Statement of Purpose
Aerospace Engineering	Not required	Not required
Bioinformatics and Computational Biology	Required for all applicants; Waived for WPI students and alumni	Required for all applicants
Biology and Biotechnology *Fall semester admission only*	Required for all applicants	Required for all applicants
Biomedical Engineering *Fall semester admission only*	Required for all applicants; Waived for WPI students and alumni	Required for all applicants
Business	GRE or GMAT required for all applicants; see page 51 for waiver information	Required for all applicants; a resume is also required
Chemical Engineering	Required for all international applicants; Recommended for all others; Waived for WPI students and alumni	Not required
Chemistry and Biochemistry	Required for all applicants; Waived for WPI students and alumni	Required for all applicants
Civil and Environmental Engineering	Required for all international applicants; Recommended for all others; Waived for WPI students and alumni	Required for Ph.D. applicants
Computer Science	Required for all applicants; Waived for WPI students and alumni	Required for all applicants
Data Science	GRE or GMAT required for international applicants; Recommended for all others; Waived for WPI students and alumni	Required for all applicants
Electrical and Computer Engineering	Required for international and Ph.D. applicants; Recommended for all others; Waived for WPI students and alumni	Required for Ph.D. applicants
Fire Protection Engineering	Required for international and Ph.D. applicants; Recommended for all others; Waived for WPI students and alumni	Required for all applicants
Interactive Media & Game Development	Recommended for all applicants	Required for all applicants; a portfolio may be submitted in addition (this is optional)
Interdisciplinary	See page 110 of the Graduate Catalog	See page 110 of the Graduate Catalog
Learning Sciences and Technologies	Strongly recommended for all applicants	Required for all applicants; a brief sample of scholarly writing is also required
Manufacturing Engineering	Required for all international applicants; Recommended for all others; Waived for WPI students and alumni	Not required
Materials Process Engineering	Required for all international applicants; Recommended for all others; Waived for WPI students and alumni	Not required
Materials Science Engineering	Required for all international applicants; Recommended for all others; Waived for WPI students and alumni	Not required
Mathematical Sciences	Recommended for all applicants; For Ph.D. and TA, GRE Mathematics Subject Test is required	Not required
Mechanical Engineering	Recommended for all applicants	Required for all applicants
Physics	Recommended for all applicants; For Ph.D. applicants GRE Physics Subject Test is required	Required for all applicants
Robotics Engineering	Required for all applicants; Waived for WPI students and alumni	Required for all applicants
Social Science and Policy Studies	Required for all applicants	Required for all applicants
STEM for Educators	Not required	Required for all applicants
Systems Engineering	Not required	Required for all applicants

Financial Assistance

Financial assistance to support graduate students is available in the form of teaching assistantships, research assistantships, fellowships, internships and loans. Entering students awarded either teaching or research assistantships or fellowships will receive official notification pertaining to the type and level of financial assistance from the Graduate Studies Office.

The academic standing of students holding awards for teaching and research assistantships is reviewed annually. To remain eligible for a graduate assistantship, a student must demonstrate acceptable progress toward degree requirements, be registered continuously, and maintain a minimum GPA of 3.00 in courses and research work (A = 4.00).

Teaching Assistantships

Teaching assistantships are awarded to graduate students on a competitive basis. They include tuition support for a maximum of 10 credit hours per semester and a monthly stipend. Teaching assistants (TAs) are generally assigned duties that support faculty in their teaching responsibilities. Typical duties of TAs include (but are not limited to) grading of undergraduate and graduate student course paperwork, supervision of undergraduate science and engineering laboratory course sections, as well as individual and small-group conference sections associated with faculty lecture courses.

TAs are required to be on campus and available for TA duties from August 15 through May 14 of each academic year. These dates correspond to the employment dates for TAs. On or before August 15th of each year, the TA should report to the department or program head to receive their TA assignments for the fall semester. The TA should report to the faculty instructors to discuss their TA assignments including the dates that they need to be available for course preparation and grading. The faculty instructors should be prepared to explain their TA expectations and the dates that the TA needs to be available. In early B term the TAs should receive their assignment for the spring semester and meet with the faculty instructors to determine their schedule and expectations. In general, TAs should be available every day the university is open. TAs are expected to work approximately 20 hours per week.

During the fall and spring breaks as well as the winter break between semesters, the TA may be required to be on campus for part of the break to assist in course preparation or grading. It is the responsibility of the faculty instructor to clearly communicate with the TAs well in advance of the break when this work is required. However, the department or program heads and the faculty instructors should work to provide a break in the TA assignments to allow the opportunity for focused research work as well as a holiday for rest and recreation. The Academic calendars are available on the registrar's website. http://www.wpi.edu/calendars/

The minimum TOEFL (internet-based test) for Teaching Assistants is 90, with no subscore (Reading, Listening, Speaking, and Writing) below 20. All Teaching Assistants will be given the SPEAK test upon arrival at WPI. If they score below the minimum (54), they will be given the opportunity to enroll in an ESL class. Students who do not meet the minimum score and do not enroll in ESL will not be allowed to continue as Teaching Assistants.

Research Assistantships

Research assistants (RAs) are selected by the faculty to participate in sponsored research projects in connection with their academic programs. Typical duties of RAs include (but are not limited to) conducting laboratory experiments and assisting in the development of theoretical advances related to faculty research projects. Research projects are typically supported by grants and contracts awarded to the university by government agencies, industrial firms or other private organizations.

RAs who perform research directly connected to their thesis/dissertation must recognize that research is a full-time professional commitment.

The financial support provided to graduate students who have been selected for an assistantship varies depending on the specific nature of the coursework, project and student's status.

Fellowships

Fellowship assistance for graduate students is available in a number of areas. Some departments offer fellowships provided by corporate gifts or philanthropic agencies. The university also directly supports graduate research programs through fellowship awards and research assistantships. Fellowship awards are administered through the Graduate Studies Office.

Completed fellowship applications are due in the Graduate Studies Office no later than January 15 for the class beginning the following fall. Criteria for eligibility is available in the Graduate Studies Office.

Educator Discounts

Educator discounts are available for in-service educators taking courses in the Master of Mathematics for Educators program, the Master of Science in Mathematics for Educators program and the Master of Science in Physics for Educators program. Educators may receive up to a 40% tuition reduction on traditional graduate student rates. Please contact the STEM Education Center to determine eligibility.

Internships

Graduate internship programs are offered in several disciplines. A graduate internship is a short-term work assignment (3 to 9 months) in residence at a company or other external organization that forms an integral part of a student's educational program.

Students participating in graduate internships must be registered in a specific course. An internship will appear on the transcript either with or without credit. Students may not participate as interns at their place of employment.

Special Notes for International Students:
An international student on an F-1 visa must maintain full-time status for the duration of their graduate program. If the student is participating in a full-time graduate internship (one that is not administered through the Career Development Center), the student must be registered for nine credits. International students with F-1 visa status may apply for two types of practical training:

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1. Curricular Practical Training (CPT): CPT is used for internships and cooperative education while students are pursuing their degrees. CPT is authorized by the university and the requirement is that the internship or co-op is an integral part of an established curriculum. Internships should be for credit.
2. Optional Practical Training (OPT): OPT is typically used by students for one year of employment after completion of degree. It can also be used in part for summer jobs or part-time employment during the academic year if employment is in the student's field of study. OPT requires approval by U.S. Customs and Immigration Services.

Student Loans

Information on financial assistance in the form of loans is available through the WPI Office of Student Aid & Financial Literacy. Students who are U.S. citizens, U.S. nationals, U.S. permanent residents, or fit into other eligible noncitizen categories set forth by the U.S. Department of Education may be eligible for federal Direct Loans, namely the Unsubsidized Loan and/or the Graduate PLUS Loan. To qualify, students must be admitted unconditionally into a graduate degree-granting program, must be enrolled on an at least a half-time basis, defined as at least five credits in a given semester, and must be making satisfactory academic progress. Satisfactory academic progress for Direct Loan borrowing is evaluated on an annual basis at the end of the spring semester. Conditionally admitted students are not eligible for federal Direct Loans.

Private student loans are also available to students enrolled in graduate programs, certificate programs or to students who are not enrolled on an at least half-time basis. A non-citizen or international student may qualify for private loans with a credit-worthy U.S. citizen or U.S. permanent resident as a cosigner.

For more information on loan programs, contact the WPI Office of Student Aid & Financial Literacy at +1-508-831-5469, and review https://www.wpi.edu/admissions/tuition-aid/applying-for-aid/graduate-students

Grading System and Academic Standards

Grading System

In order to assess progress throughout the graduate program, grades are assigned to the student's performance in course, project and thesis work, except in doctoral dissertation, which will be judged as ACCEPTED or REJECTED. Academic achievement in all other work is based on the following grading system:

A Excellent
B Good
C Pass
D Unacceptable for graduate credit
F Fail
AU Audit
NC No credit (only for thesis work); will not be recorded on transcript
P Pass; unacceptable for graduate credit
I Incomplete; transition grade only; becomes grade of F if not changed by instructor within 12 months
W Withdrawal
SP Satisfactory progress; continuing registration in thesis/dissertation/directed research
CR Credit for work at another institution
UP Unsatisfactory progress; this grade remains on the file transcript
AT Attended

Academic Standards

Students must maintain high academic standards in all their program activities. After attempting 12 credit hours, all students must maintain an overall grade point average (GPA) above 2.75 to be considered as making satisfactory progress. If a student's overall GPA falls to 2.75 or below, the student and advisor are notified by the Registrar that the student is not making satisfactory progress.

If the overall GPA of any student falls below 2.65, the Registrar will inform the student that all future registrations will be given grades only on a pass/fail basis unless the department Graduate Committee intervenes.

If the overall GPA of any student falls below 2.50, the student is removed from the program unless the department Graduate Committee intervene.

A student is expected to expend at least 56 hours of total effort (including classroom time) for each graduate credit. This means that a student in a 3-graduate credit 14-week course is expected to expend at least 12 hours of total effort per week. A student in a 2-graduate credit 7-week course is expected to expend at least 16 hours of total effort per week.

Grade Point Average (GPA)

Grades are assigned the following grade points:
A = 4.0, B = 3.0, C = 2.0, D = 1.0 and F = 0.0. The grade point average is calculated as the sum of the products of the grade points and credit hours for each registered activity (including courses, independent studies, directed research, thesis research and dissertation research) in the average, divided by the total number of credit hours for all registered activities in the average. If a student takes the same course more than once, the course enters the GPA only once, the most recent grade received for the course being used in the average.

A student's overall GPA is calculated on the basis of all registered activities taken while enrolled as a graduate student at WPI. WPI graduate courses taken before a student had status as a degree-seeking graduate student are included in the over-all GPA. A student's program GPA is calculated on the basis of those WPI courses listed by the student on the student's Application for Graduation form. The transcript will report the overall GPA.

Courses transferred from elsewhere for graduate credit (for which a grade of CR is recorded on the WPI transcript), and courses taken to satisfy undergraduate degree requirements or to remove deficiencies in undergraduate preparation,

are not included in either GPA. Registered activities in which the student receives grades of AU, NC, P, I, W, SP or UP are not included in either GPA.

Only registered activities in which a grade of A, B, C or CR was obtained may be used to satisfy courses or credit requirements for a graduate degree.

Grade Appeal and Grade Change Policy

The Student Grade Appeal Procedure affirms the general principle that grades should be considered final. The principle that grades for courses, thesis credit and dissertation credit should be considered final does not excuse an instructor from the responsibility to explain his or her grading standards to students, and to assign grades in a fair and appropriate manner. The appeal procedure also provides an instructor with the opportunity to change a grade for a course or project on his or her own initiative. The appeal procedure recognizes that errors can be made, and that an instructor who decides it would be unfair to allow a final grade to stand due to error, prejudice or arbitrariness may request a change of grade for a course or project without the formation of an ad hoc committee. An instructor may request a grade change by submitting a course, thesis credit or dissertation credit grade change request in writing to the Registrar at any time prior to a student's graduation.

The purpose of the Grade Appeal Policy is to provide the student with a safeguard against receiving an unfair final grade, while respecting the academic responsibility of the instructor. Thus, this procedure recognizes that:

- Every student has a right to receive a grade assigned upon a fair and unprejudiced evaluation based on a method that is neither arbitrary nor capricious; and,
- Instructors have the right to assign a grade based on any method that is professionally acceptable, submitted in writing to all students, and applied equally.

Instructors have the responsibility to provide careful evaluation and timely assignment of appropriate grades. Course and project grading methods should be explained to students at the beginning of the semester. WPI presumes that the judgement of the instructor of record is authoritative and the final grades assigned are correct.

A grade appeal shall be confined to charges of unfair action toward an individual student and may not involve a challenge of an instructor's grading standard. A student has a right to expect thoughtful and clearly defined approaches to course and research project grading, but it must be recognized that varied standards and individual approaches to grading are valid. The grade appeal considers whether a grade was determined in a fair and appropriate manner; it does not attempt to grade or re-grade individual assignments or projects. It is incumbent on the student to substantiate the claim that his or her final grade represents unfair treatment, compared to the standard applied to other students. Only the final grade in a course or project may be appealed. In the absence of compelling reasons, such as clerical error, prejudice, or capriciousness, the grade assigned by the instructor of record is to be considered final.

Only arbitrariness, prejudice, and/or error will be considered as legitimate grounds for a grade change appeal.

Arbitrariness: The grade awarded represents such a substantial departure from accepted academic norms as to demonstrate that the instructor did not actually exercise professional judgment.

Prejudice: The grade awarded was motivated by ill will and is not indicative of the student's academic performance.

Error: The instructor made a mistake in fact.

This grade appeal procedure applies only when a student initiates a grade appeal and not when the instructor decides to change a grade on his or her own initiative. This procedure does not cover instances where students have been assigned grades based on academic dishonesty or academic misconduct. Academic dishonesty or misconduct are addressed in WPI's Academic Honesty Policy. Also excluded from this procedure are grade appeals alleging discrimination, harassment or retaliation in violation of WPI's Sexual Harassment Policy, which shall be referred to the appropriate office at WPI as required by law and by WPI policy.

The Grade Appeal Procedure strives to resolve a disagreement between student and instructor concerning the assignment of a grade in a collegial manner. The intent is to provide a mechanism for the informal discussion of differences of opinion and for the formal adjudication by faculty only when necessary. In all instances, students who believe that an appropriate grade has not been assigned must first seek to resolve the matter informally with the instructor of record. If the matter cannot be resolved informally, the student must present his or her case in a timely fashion in the procedure outlined below. Under normal circumstances, the grade appeal process must be started near the beginning of the next regular academic semester after the disputed grade is received.

Student Grade Appeal Procedure

1. A student who wishes to question a grade must first discuss the matter with the instructor of record within one week after the start of the next regular academic semester (fall or spring) or term (A, B, C or D) after receiving the grade. Late appeals will only be reviewed at the discretion of the Faculty Review Committee (FRC). In most cases, the discussion between the student and the instructor should suffice and the matter will not need to be carried further. The student should be aware that the only valid basis for grade appeal beyond this first step is to establish that an instructor assigned a grade that was arbitrary, prejudiced or in error.
2. If the student's concerns remain unresolved after the discussion with the instructor, the student may submit a written request to meet with the appropriate Department Head or Program Coordinator within one week of speaking with the instructor. The appropriate Department Head or Program Coordinator will meet with the student within one week and, if he or she believes that the complaint may have merit, with the instructor. After consultation with the appropriate Department Head or Program Coordinator, the instructor may choose to change the grade in question or leave the grade unchanged. The Department Head or Program Coordinator will communicate the result of these discussions to the student.

3. If the matter remains unresolved after the second step, the student should submit a written request within one week to the Provost's Office to request an ad hoc committee for Appeal of a Grade. The Provost's representative (the Dean of Graduate Studies, or alternate) will meet with the student and will ask the Faculty Review Committee (FRC) to appoint the ad hoc committee for Appeal of a Grade. The Chair of the FRC will select the members of the ad hoc committee and serve as its non-voting chair. The ad hoc committee for appeal of a course, thesis credit or dissertation credit grade will be composed of three faculty members. The first member will be the Department Chair, Program Coordinator or Departmental Graduate Coordinator from the instructor's Department. If all three have a conflict of interest, the Provost's representative will serve on the ad hoc committee. The remaining two members will be two FRC members with no conflicts of interest with either the student or the instructor. Apparent conflicts of interest would include the student's thesis or dissertation advisor, members of the student's graduate committee, and faculty members with close research collaboration or project advising relationships with the instructor. The Chair of the FRC requests a written statement from the student and a written response from the instructor. The ad hoc committee examines the written information and may gather additional information as it sees fit.
4. Through its inquiries and deliberations, the ad hoc committee is charged to determine whether the grade was assigned in a fair and appropriate manner or whether clear and convincing evidence of arbitrariness, prejudice, and/or error might justify changing the grade. The ad hoc committee will make its decisions by a majority vote.
5. If the ad hoc committee concludes that the grade was assigned in a fair and appropriate manner, the ad hoc committee will report its conclusion in writing to the student and the instructor. The decision of the ad hoc committee is final and not subject to appeal.
6. If the ad hoc committee determines that compelling reasons exist for changing the grade, it would request that the instructor make the change, providing the instructor with a written explanation of its reasons. At this point, the instructor may change the grade. If the instructor declines to change the grade, he or she must provide a written explanation for refusing. If the ad hoc committee concludes that the instructor's written explanation justifies the original grade, the ad hoc committee will report this in writing to the student and instructor and the matter will be closed. If the ad hoc committee concludes that it would be unjust to allow the original grade to stand, the ad hoc committee will then determine what grade is to be assigned. The new grade may be higher than, the same as, or lower than the original grade. Having made this determination, the three members of the committee will sign the grade change form and transmit it to the Registrar. The instructor and student will be advised of the new grade. Under no circumstances may persons other than the original faculty member or the ad hoc committee change a grade. The written records of these proceedings will be filed in the student's file in the Registrar's Office.

Project, Thesis, and Dissertation Advising

A graduate project, thesis, and/or dissertation must include a faculty advisor-of-record at the time of initial registration.

The only faculty members who may, by virtue of their appointment, automatically be the formal advisors-of-record for graduate projects or independent study activities (ISGs, theses, dissertations, etc.) are:

1. tenure/tenure track faculty,
2. professors of practice, or
3. others who have at least a half-time, full-year faculty appointment, with advising of independent work as part of their contractual load.

Individuals holding other faculty appointments, such as part-time adjuncts or non-instructional research professors, may co-advise and indeed are encouraged to do so where appropriate.

Department heads wishing to authorize anyone with appointments other than these three categories as an advisor of record for projects, theses, or independent studies must first obtain agreement from the Dean of Graduate Studies. (In their absence, please refer the request to the Associate Provost for Academic Affairs.)

Plan of Study

After consultation with and approval by the advisor, each admitted student must file a formal Plan of Study with the department within the first semester if full-time, and within the first year if part-time. Program changes are implemented by advisor and student. Copies of the revised Plan of Study will be maintained in department files.

Enrollment and Registration

The basic requirement for enrollment in a given course is a bachelor's degree from an accredited institution in a relevant field of science or engineering. Although those with management backgrounds may enroll in graduate management courses, no prior management study is required. Persons who have been admitted to graduate study at WPI are given first priority in course registration. Persons not holding a bachelor's degree, but who might qualify through training or experience, may be allowed to enroll on either a credit or audit basis with permission of the instructor. Registration for graduate courses is on a space-available basis for nonadmitted students.

Graduate students are expected to enroll in graduate courses or thesis credit on the registration days designated in the WPI academic calendar. Registration on days not designated will result in additional fees.

Enrollment in a course or courses, and satisfactory completion of those courses, does not constitute acceptance as a candidate for any graduate degree nor does it indicate admission to any graduate program. For students seeking advanced degrees, or graduate certificates, formal admission to a graduate program is required.

International Students

International students are required to enroll no later than the final day of the add/drop period. Students must be enrolled by this time in order to be registered in the SEVIS database and to remain in legal immigration. Failure to enroll in a timely manner could jeopardize a student's legal status and ability to lawfully remain in the U.S.

Degree-Seeking Student Enrollment

Graduate students must be registered for the semester in which degree requirements are completed. For master of science programs requiring a thesis and all Ph.D. programs, students must register for a minimum of 1 semester credit hour.

For master of science programs that do not require a thesis, all students must be registered for all remaining credits in the final semester of study.

Full-time degree-seeking graduate students are expected to be continuously registered during their graduate school careers, excluding the summer semester. Full-time degree seeking students who interrupt their studies and are not on an approved leave of absence will be marked 'inactive' in any fall or spring semester in which there is no registration or credit activity. Inactive status means that students do not have access to WPI buildings, services or coursework.

In recognition of the competing responsibilities faced by part-time students, WPI allows one semester without credit activity to elapse before active status is revoked. Part-time degree-seeking graduate students will be marked inactive if one semester elapses with no credit activity and the registration period of the subsequent semester ends without registration or credit activity.

Inactive students will need to complete a readmission form through the Registrar's Office. See "Readmission from Leave of Absence" section below.

Official Withdrawal

Students who wish to terminate their degree programs must complete the Graduate Withdrawal Form available on the Registrar website and submit it to the Registrar's Office. Any registrations in semesters or terms that have begun before the certified date of last attendance will receive a grade of W and the student will be exempted from academic review. Any registrations in semesters or terms that have not begun before the certified date of last attendance will be dropped. For official start dates of semesters and terms, see the Academic Calendar. For tuition refund information, see the "Tuition and Fees" section.

Note: This applies to students officially withdrawing from the University; for an individual course withdrawal, please refer to the Course Changes section for policy and refund information.

Institutional Leave of Absence

Full-time students who wish to take a temporary leave from their degree programs and part-time students who wish to take more than one contiguous semester off must complete the Leave of Absence Form available on the Registrar website and submit it to the Registrar's Office. Students should inform themselves about consequences to financial aid, visa status, housing, and other considerations before taking an institutional leave of absence. Any registrations in semesters or terms that have begun before the certified date of last attendance will receive a grade of W and the student will be exempted from academic review. Any registrations in semesters or terms that have not begun before the certified date of last attendance will be dropped. For official start dates of semesters and terms, see the Academic Calendar. For tuition refund information, see the "Tuition and Fees" section.

Note: This applies to students taking a full leave from the University; for an individual course withdrawal, please refer to the Course Changes section for policy and refund information.

Readmission from Leave of Absence

To return, a student must fill out the Graduate Readmission Form available on the Registrar website and submit it to the Registrar's Office with all required signatures at least 30 days prior to the start of the semester in which they plan to return.

Military Leave of Absence

WPI graduate students who are called to active duty by the United States military shall receive a 100% refund for the uncompleted semester at the date of the notice. If such students have a loan obligation to WPI they will be granted an in-school deferment status during the period of active duty service, not to exceed a total of three years. To initiate the process to be classified "on leave for military service," a student must fill out a Leave of Absence form available on the Registrar website indicating that he/she is requesting school deferment status while being called to active duty. A copy of the official call to active duty notice from the military must be included with this request and be submitted to the Registrar's Office.

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If the student has paid a tuition bill with proceeds from either a subsidized or an unsubsidized Federal Stafford Loan and has received a refund for either or both of the loans, the student shall be responsible for any overpayment of funds. It is therefore necessary for the student to contact the lender(s) upon withdrawal.

Non-degree Student Enrollment

Individuals with earned bachelor's degrees may wish to enroll in a single course or a limited number of courses prior to applying for admission. Non-degree students may choose to be graded conventionally (A, B, C), or on a pass/fail basis. Pass/Fail grading must be chosen at the time of registration, and courses taken on the pass/fail basis are not transferable to any master's degree program.

Non-admitted students may take a maximum of four graduate courses and receive letter grades in most departments. See department descriptions for specific information. Once these maximums are reached, additional course registrations will be changed to pass/fail and may not be used for degree credit.

The fact that a student has been allowed to register for graduate courses (and earn credit) does not guarantee that the student will be admitted to that department's certificate or degree program at a later date. Students are therefore encouraged to apply for admission to a degree or certificate program prior to any course registration.

Non-degree Student Course Registration

Nondegree-seeking students register for courses in the same manner as all other students. However, degree-seeking students have preference in registering for courses with limited enrollments. Non-degree graduate students are considered active only in those semesters during which they have a current registration and credit activity. They are marked as inactive in the semester following the conclusion of their credit activity, including the summer semester, provided there is no new registration.

Auditing Courses

Graduate students primarily interested in the content of a particular course may register as auditors. Students are charged a 50% reduced tuition rate per semester hour to audit a course. There is **no credit** and **no grade** awarded for classes that are audited. Students cannot audit thesis and project work.

Audit registrants are encouraged to participate in the courses, but typically do not submit written work for evaluation. Often professors will accept written work of audit registrants, but this is left to the discretion of the instructor.

A student may change from credit to audit registration, but may not change from audit to regular credit registration. To change to audit registration for any graduate course, the student must complete an audit form (available in the Registrar's Office) within the first three weeks of class. No tuition or fees will be returned to students who change to audit registration, i.e., the full tuition rate applies.

Definition of Full-Time and Part-Time Status

If a student is registered for 9 or more credits, the student is deemed to be a full-time student for that semester. If a student needs fewer than 9 academic credits to complete degree requirements, registration for the number of credits required for completion of the degree gives the student full-time status. A student pursuing a master's degree, whose Plan of Study shows completion of all degree requirements within a single two-year period, retains full-time status so long as the student complies with that Plan of Study. A student officially enrolled in a graduate internship program has full-time status during the internship period. If a student has completed the minimum number of credits required for a degree, and is certified by the department or program to be working full-time toward the degree, enrollment in 1 credit of dissertation research for a student seeking the doctorate establishes full time status. For students seeking a master's degree, 1 credit of thesis research establishes the student's full-time status with department certification. For the purposes of this rule, the semesters are fall and spring.

Transcripts

Transcripts may be requested, and there is a fee associated with each transcript. For more information, please visit www.wpi.edu/+registrar.

Course Changes

There is an add/drop period at the start of each term and the exact deadlines depend on whether the course follows a 7-week schedule or a 14-week schedule.

For 7-week courses (undergraduate and graduate), a student can add a course without a fee through the fifth day of classes. On the sixth through the tenth day of classes, students can add courses (with instructor approval) with a $100 late fee. Students can drop courses on days 1-10 of each term without incurring a late fee. For undergraduates in 7-week courses, no adds or drops are allowed after the tenth day of the term. For graduate students in 7-week courses who drop a course after the tenth day, but before the end of the fifth week of the term, a W (Withdrawal) will be assigned. No tuition or fees will be refunded after the tenth day of the term.

For 14-week courses (undergraduate and graduate), students can make course changes (add or drop) without penalty through the tenth day of the semester. A $100 late fee will be charged for course adds after the tenth day of the semester and instructor permission is required. No drops are allowed after the tenth day of the semester; for graduate students, course withdrawals are permitted through the tenth week of the semester, and a grade of W (Withdrawal) will be assigned. No tuition or fees will be refunded after the tenth day of the semester. Consult the University calendar for specific dates.

For 10-week courses (undergraduate and graduate), students can make course changes (add or drop) without penalty through the tenth day of the semester. A $100 late fee will be charged for course adds after the tenth day of the semester and instructor permission is required. No drops are allowed after the tenth day of the semester; for graduate students, course withdrawals are permitted through the seventh week of the semester, and a grade of W (Withdrawal) will be assigned. No tuition or fees will be refunded after the tenth day of the semester.

Note: If a degree-seeking student is dropping or withdrawing from all registered course activity, they must either take an institutional leave of absence or officially withdraw from the University.

Tuition and Fees

Tuition for all courses taken by graduate students is based on a $1,457 fee per credit hour for the 2017-2018 academic year. The Graduate Student Organization Fee is $30.00 for full-time students and $15.00 for part-time students each semester. See https://www.wpi.edu/offices/bursar/tuition for current tuition and fee information.

Tuition Refunds for Leaves and Withdrawals

Tuition refunds will follow the schedule below, based on the certified last date of attendance, for Institutional Leave of Absences and Official Withdrawals. Any registrations in semesters or terms that have not begun before the certified date of last attendance will be dropped. Weeks are counted from the official start date of the semester.

Last Date of Attendance During:	Tuition Refund %
Week 1	100%
Week 2	100%
Week 3	80%
Week 4	60%
Week 5	40%
Week 6	20%
Week 7 and after	0%

Note: This applies to students taking a leave of absence or officially withdrawing from the institution; for an individual course withdrawal, please refer to the Course Changes section for policy and refund information.

WPI Alumni Tuition Incentive

WPI alumni who completed a bachelor's degree at WPI within the last five years are eligible for the tuition incentive program. The program is designed to help students complete their Master's degree program at an accelerated rate.

To participate, you have to be admitted and enrolled as a full-time student in one of WPI's M.S. degree programs. In each semester of your first year of graduate study, you will pay for nine credits of course work, but you may register for as many as eighteen credits in each semester. In other words, you can take up to nine credits beyond the nine-credit, full-time threshold in each semester of your first year at no extra cost.

All eligible students are pre-coded to participate, so all you have to do is register for the courses you want. If you believe you are eligible but have been charged for extra courses, please contact the Bursar's office.

The following restrictions apply:

- Students in the MBA program are not eligible
- Students are only eligible during their first year of full-time Masters-level graduate study
- Students are only eligible during their first two consecutive semesters of Masters-level study
- Funded students (TAs, RAs, etc) are not eligible

If you have questions, please contact the Office of Graduate Admissions at grad@wpi.edu.

Audit Rate

A 50% reduced tuition rate per semester hour for the 2017-2018 academic year is available for those who wish to audit a course. Audit registration cannot be changed to credit once the semester has started.

Tuition Payments & Billing

WPI sends electronic bill statements (eBill) to the WPI email address assigned to each student. Bills are sent in the fall and spring semesters. It is important to view each new eBill you receive as changes could have occurred in your account.

Tuition must be paid in full by the specified due date on the electronic bill (eBill) statement. Students that register within one week prior to the eBill due date are required to pay at the time of registration. Students remit payment online with a checking account (no fee) or via credit card (2.75% fee). For international credit card or wire payments visit https://www.flywire.com/school/wpi. For information on the eBill process or payment options, please visit www.wpi.edu/+bill.

Late Fees

Late fees of up to $250 will be assessed on balances and accounting holds will be placed on accounts. The first late fee is assessed after the initial due date for the bills, the second is typically assessed mid semester for outstanding balances.

Monthly Payment Option

A monthly payment plan is available for each semester. Payments will be divided into equal monthly payments. There is an annual or semester enrollment fee for use. However, there are no additional charges or interest (late fees or returned payment fees may apply). For more information, visit Tuition Management Systems (TMS) at www.afford.com or contact the Bursar's Office at www.wpi.edu/+bill.

Health Insurance

All full-time graduate students must be covered by health and accident insurance equivalent to that offered under the WPI Student Health Insurance Plan. Students must complete a waiver form online annually if they wish to not purchase the WPI offered plan. Optional coverage for a spouse or dependent is available. Please contact the Bursar's Office www.wpi.edu/+bill for further information.

Visit us any time at:
www.wpi.edu/+registrar

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Degree Requirements

The following are WPI's minimum requirements for advanced degrees. The general requirements for all advanced degrees must be satisfied to earn any advanced degree. The additional requirements for specific degrees must be satisfied in order to earn the specified degree, regardless of the field in which the degree is earned. Please review department requirements for more specific information.

General Requirements for All Advanced Degrees

All degree requirements must be satisfied before the degree is awarded. Exceptions to general and specific degree requirements or to other rules may be made, but only by the Committee on Graduate Studies and Research (CGSR).[1] Requests for exceptions are to be made by written petition to that committee.

At the time the degree is awarded, the student must have been admitted to the graduate program of the degree-granting program. Administratively, a degree-granting program may be a department or a program.

A minimum of two-thirds of the required graduate credit for an advanced degree must be earned at WPI.

All degree and certificate programs require a minimum program GPA of 3.0.

In applying for graduation, the student must specify by year which graduate catalog contains the rules being satisfied. These rules may be those in place on the date of the student's matriculation, those in place on the date of the student's application for graduation, or those in place in a single graduate catalog in effect between the dates of matriculation and graduation.

After the Application for Degree is submitted, all advanced degrees are subject to the final approval of the Registrar's Office, which determines if the student has satisfied the letter and intent of the requirements for advanced degrees.

The Registrar's Office submits a candidates list to CGSR who make their recommendations for the approval of advanced degrees to the faculty of the institute, which in turn recommends to the president and trustees for their final approval the names of students who should be awarded advanced degrees.

Requirements for the Master of Business Administration and Master of Mathematics for Educators appear under the descriptions of the awarding programs.

General Requirements for the Master of Science and Master of Engineering

The student must obtain a minimum of 30 credit hours of acceptable course, thesis or project work.

If a thesis is required by the student's program, it must include at least 6 credit hours of research directed toward the thesis, in a project resulting in the completion of an M.S. thesis.

A student completing a master's degree with a thesis option is required to make a public presentation of the thesis. Departments may, at their option, extend the presentation to include a defense of the thesis.

The student must obtain a minimum of 21 credit hours of graduate level courses or thesis (18 credit hours for students in the Combined Bachelor's/Master's Program), including at least 15 credit hours of graduate level courses or thesis in the major field of the student. Other courses (to make up the minimum total of 30 credit hours) may include advanced undergraduate courses approved by the student's program. Such courses are normally considered to be those at the 4000 level. The use of advanced undergraduate courses for satisfaction of graduate degree requirements must be approved by the student's program. A 1/3-unit WPI undergraduate course taken for graduate credit is assigned 2 credit hours of graduate credit. A graduate student registered for graduate credit in an undergraduate course may be assigned additional work at the discretion of the instructor.

General Requirements for the Doctorate

The student must demonstrate to the faculty high academic attainment and the ability to carry on original independent research.

The student must complete a minimum of 90 credit hours of graduate work beyond the bachelor's degree, or a minimum of 60 credit hours of graduate work beyond the master's degree, including in either case at least 30 credit hours of research.

The student must establish residency by being a full-time graduate student for at least one continuous academic year.

The student must attain status as a doctoral candidate by satisfying specific degree requirements in the student's field.

The student must prepare a doctoral dissertation and defend it before a Dissertation Committee, at least two of whose members must be from the student's program and at least one of whose members must be from outside the student's program. After a successful defense, determined by a majority vote in the affirmative by the Dissertation Committee, the dissertation must be endorsed by those members of the Dissertation Committee who voted to approve it. The completed dissertation must follow in format the instructions published by the library (see page 23). After final approval for format of the dissertation, the Provost will notify the Registrar that the dissertation has been approved.

1 CGSR—The Committee on Graduate Studies and Research (CGSR) is concerned with all post-baccalaureate programs of the University, and reviews and recommends changes in WPI policies on goals, student recruitment, admissions, academic standards, teaching and research assistantships, scholarships and fellowships. It also makes recommendations to the faculty and administration on new graduate programs and courses, and changes in programs and courses. The committee acts on admission of graduate students to degree candidacy, dismissal for failure to meet academic standards, and student petitions on academic matters. It brings to the faculty for action the names of students whom it has determined are eligible for post-baccalaureate degrees. The committee reviews and recommends changes in policy on the funding, promotion and conduct of research at WPI.

2 GPA—The Grade Point Average (GPA) is calculated as the sum of the products of the grade points and credit hours for each registered activity, in the average, divided by the total number of credit hours for all registered activities in the average. Grade points are as follows: A = 4.0; B = 3.0; C = 2.0; D = 1.0; and F = 0.0.

Once a student has satisfied the departmental candidacy requirements, the student will be permitted to enroll for dissertation credits. Prior to completion of candidacy requirements, a student may enroll for no more than 18 credits of directed research.

General Requirements for the Combined Bachelor's/ Master's Degree Program

Only registered WPI undergraduates may enter the Combined Bachelor's/Master's Program. To enter, a student must submit an application and required support materials to WPI's Office of Graduate Admissions, preferably in the junior year. Admission to the combined program is made by the faculty of the program that awards the graduate degree. A student in the combined program continues to be registered as an undergraduate until the bachelor's degree is awarded.

While in the combined program, a student may continue to enroll in courses or projects toward the undergraduate degree; the student may also register for graduate courses, projects, directed research or thesis credits toward the master's degree.

A student in the combined program may, within the program limit and with prior approval, use a limited number of the same courses toward the bachelor's and master's degrees. The limitation is computed from the graduate credit hours for each course. Courses whose credit hours total no more than 40% of the credit hours required for the master's degree, and which meet all other requirements for each degree, may be used to satisfy requirements for both degrees. Such courses are recorded on the transcript using the credit hours/ units and grades appropriate at the graduate or undergraduate levels. For students in the combined program, approved undergraduate courses are assigned graduate credit with a conversion rate of 1/3 WPI undergraduate unit = 2 credit hours. Graduate courses applied toward the undergraduate degree are awarded undergraduate credit with a conversion rate of 1 credit hour = 1/6 undergraduate unit.

Students in the combined program may use advanced undergraduate courses to satisfy graduate degree requirements. The academic department decides which courses may be used in this way. Faculty members teaching these advanced undergraduate courses may impose special requirements.

If the programs awarding the bachelor's and master's degrees are not the same, the program awarding the graduate degree may require that the student's major qualifying project relate in some way to the graduate program's discipline. The graduate program may also make other requirements as it deems appropriate in any individual case. Additional requirements appear within each department's section in this catalog.

To obtain a master's degree via the combined program, the student must satisfy all requirements for that master's degree. To obtain a bachelor's degree via the combined program, the student must satisfy all requirements for that bachelor's degree.

The time limit for completing the combined program varies by department from one to four years. See department description for full information.

Limitation of Time to Complete Degree

Students must complete degree requirements within the following timelines:

Degree	Time Limit
Graduate or Advanced Certificate	Within 3 years of matriculation
Master's Degree (M.S., MENGR, MME)	Within 5 years of matriculation
M.B.A.	Within 7 years of matriculation
Ph.D.	Within 10 years of matriculation

Approved leaves of absence do not stop the clock for the completion of the degree. Students who require more time to complete their degree must petition Dean to continue.

Transfers and Waivers

A student may petition to use graduate courses completed at other accredited, degree-granting institutions to satisfy WPI graduate degree requirements. A maximum of one-third of the credit requirements for a graduate degree may be satisfied by courses taken elsewhere and not used to satisfy degree requirements at other institutions.

Students should submit their petitions to their academic department or program; once they are approved they are filed with the Registrar.

To ensure that work completed at other institutions constitutes current practice in the field, a WPI program may set an expiration date on transfer credit. After this date, the course may not be counted towards a WPI degree.

Transferred courses are recorded on the student's WPI transcript with the grade CR and are not included in the calculation of grade point averages. Grades earned in Biomedical Consortium courses, however, are recorded on the transcript as if they were taken at WPI itself.

A student with one or more WPI master's degrees who is seeking an additional master's degree from WPI may petition to apply up to nine prior graduate credits towards the requirements for the subsequent degree.

A student who withdraws from a graduate program and is later readmitted may apply courses and other credits completed before the withdrawal toward the degree. The admitting program will determine at the time of readmission which courses taken by the student may be applied toward the degree and the latest date those courses may be applied. There is no limit, other than that imposed by the program, on the number of credits a readmitted student may use from prior admissions to the same degree program.

With the appropriate background, a student may ask permission to waive a required course and substitute a specified, more advanced course in the same discipline. Requests are subject to approval by the student's program and must be filed with the Registrar within one year of the date of matriculation in the program. A program may waive (with specified substitutions) up to three required courses for a single student.

Acceptability of Credit Applicable to an Advanced Degree

Graduate level credit, obtained from courses, thesis and project work, may include:

- Coursework included in the approved Plan of Study.
- Coursework completed at the graduate level and successfully transferred to WPI from other accredited, degree-granting institutions (see Transfers and Waivers).
- Graduate coursework completed at the undergraduate level at WPI and not applied toward another degree.
- ***A maximum of one-third of the credit requirements*** from a previous master's degree ***at WPI*** may be used in partial fulfillment of the requirements for a second master's degree at WPI.
- Coursework approved for the Combined WPI Bachelor's/Master's Program.
- Project work done at the graduate level at WPI.
- Thesis work done at the graduate level at WPI.

Departments and programs may limit the use of credit in any of these areas depending upon their specific departmental requirements.

Theses and Dissertations

WPI is a member of the Networked Digital Library of Theses and Dissertations. This organization is dedicated to "unlocking access to graduate education" by making the full text of theses and dissertations available online.

Students are required to submit an electronic version entirely through the Web.

Most documents will be made available to the general public via the Web, but individual authors and their advisors may choose to restrict their works to be accessible only by members of the WPI community or to be completely unavailable for a period of up to five years. Factors in this decision should include copyright, intellectual property and patenting concerns. Students should discuss these issues thoroughly with their advisors and committee members as early in the process as possible.

The following are required for proper submission of electronic theses and dissertations (ETDs):

1. The printed and signed copy of the ETD Approval Form
2. A printed copy of the title page, with all appropriate faculty and student signatures
3. The thesis or dissertation converted to PDF and uploaded via the ETD Website

Items 1 and 2 should be submitted to the Registrar's Office. Students will receive a confirmation from the ETD submission system once it has been accepted. The Registrar's Office will be notified simultaneously of the ETD confirmation.

Extensive information about creating and submitting ETDs is available on the ETD website, www.wpi.edu/+etd.

Thesis Binding

Students and departments may wish to retain a bound paper copy of theses and dissertations. Gordon Library will be happy to do this for you at your expense. Information on thesis binding can be found online at http://wpi.edu/Pubs/ETD/binding.html.

Student Services

Facilities and Services

Bookstore

The bookstore, located on the second floor of the Rubin Campus Center, is open during the first days of classes from 8:00 a.m. to 7 p.m. During the rest of the school year, hours of operation are 8 a.m. to 7 p.m. Monday through Thursday, 8 a.m. to 5 p.m. Friday, and 11 a.m. to 5 p.m. on Saturday.

Textbooks for off-campus courses may be purchased at the first meeting of each course. Payment may be made by cash, check or credit card. Additionally, textbooks may be purchased online at http://wpi.bncollege.com.

For more information please call (508) 831-5247 or e-mail bkswpi@bncollege.com.

Student Health Center

In addition to purchasing health insurance, graduate students may also make use of WPI's Student Health Center for an annual fee of $370 . By choosing this option, you can have a doctor at the Center serve as your primary care physician. You may also then use the center on a walk-in basis during its normal hours (weekdays 8:00am to 5:00pm). You can learn more about WPI's Student Health Center at www.wpi.edu/+Health.

WPI Police

Personal safety information, security practices at WPI and the University's crime statistic information can be obtained by visiting the campus police Website. Students can also obtain a copy of the University's "Right To Know" brochure by contacting the WPI Police Department at 508-831-5433.

Graduate students are entitled to parking permits for the Boynton Street parking lot located behind the library for an annual fee. Parking is on a first-come, first-served basis. Parking is also available on the city streets surrounding the campus. Be sure to obey parking signs, as enforcement in Worcester is strict. The city's winter parking regulations are available on the WPI police website, as well.

Decals may be purchased at the WPI Police Department located at Founders Hall in the Lower Level. WPI Police also has prepared a brochure on parking regulations that is available on-site or on-line at http://www.wpi.edu/offices/police/parking.html.

Career Development Center

The Career Development Center (CDC) at WPI assists graduate students in the development of lifelong skills related to careers and the job search process. The CDC provides resources and support to graduate students on resume/CV writing, cover letter critiques, internship and job search strategies, interviewing skills/mock interviews, advanced degree pursuit, career advising, job offer evaluation and negotiation skills, and more. Support to graduate students is available through appointments with a CDC staff member, walk-ins, and workshops. For distance students, telephone and Skype appointment options are available. The CDC is available for lifetime service and support to alumni, free of charge.

Every graduate student has a Job Finder account (www.wpi.edu/+jobfinder) to search for companies and jobs, gain access to subscription resources (Career Shift, Going Global, Career Search, MyPlan), access upcoming workshops and corporate events, and more. All appointments are scheduled through Job Finder, via "Request an Appointment" in the Shortcuts menu.

To contact the CDC, call 508-831-5260, email cdc@wpi.edu, or visit us at the Project Center, Lower Level.

Class Cancellation

When all classes are cancelled (severe weather during the midday period, forecast to last through evening) cancellation will be broadcast on radio stations WTAG, WSRS, WAAF, WFTQ, WKOX and WBZ. Information will also be posted on the university website and on the cancellation hot line at 508-831-5744.

Information Technology Resources

WPI Information Technology Services manages a wide range of information technology resources for the WPI community to support teaching, learning, research and student life. The WPI computer account provides students access to technology resources including personal network file storage and acts as their WPI virtual identity while the student is actively registered.

Software

Numerous software packages including academic courseware are available to students via:

- public computer labs
- remote services (Remote Desktop and Terminal Servers)
- network download for some applications
- online store for discounted purchase

WPI partners with Microsoft to provide students access to current Microsoft operating system with business productivity software, and anti-virus protection for use on their personal computers.

Computer Labs and Printing

Hundreds of computers are available across campus for student use with many located in open access labs within academic buildings and the Gordon Library. Public computer labs offer a consistent user interface, software profile, and network access to centralized personal file storage. The Gordon Library houses a Multimedia Lab for high-end digital editing as well as the centrally located Information Commons Print Center that is available to meet students' scanning and printing needs.

Collaboration & Learning Resources

Collaboration and learning are supported through specialized software and applications, technology-enhanced spaces, and equipment loans.

- Tech Suites: Technology-enhanced meeting spaces designed for student project group use
- Learning Management System: Canvas course websites

- Tools: Exchange Online (email/calendar/contact management), Skype for business, SharePoint
- Equipment Loans: including laptops, digital cameras, camcorders, audio recorders, hard drives, projectors, etc.
- Electronic classrooms and electronically enabled conference rooms
- Web-conferencing tools allow global participants to conduct meetings in a web-based environment in real-time via the Internet

Technology Support and Instruction

Technology Service Desk

Gordon Library, Main Floor;
508-831-5888; its@wpi.edu; it.wpi.edu

- In-person technology support provided at the Service Desk
- Requests for assistance can be submitted via phone, email or web

Academic Technology Center

Fuller Labs, Room 117; 508-831-5220;
atc@wpi.edu

- In-person technology support on audio-visual equipment loaned out for multi-media projects and campus events sponsored by WPI student organizations
- Large format poster printing
- Digital signage system for announcements pertaining to campus events

Academic and Research Computing

Higgins Labs, Room 232;
archelp@wpi.edu; arc.wpi.edu

- Instructor led scientific and engineering software applications training
- Manage academic software and applications campus wide
- Rapid prototyping/3D printing services and consultation
- Large format poster printing
- The Design Studio, HL234, offers powerful workstations for CAD/FEA/FEM projects and coursework.
- Data Management and access to cloud collaboration space
- High Performance Computing (HPC) hardware, including single servers and clusters, available for a range of computational simulations

Infrastructure Services

Physical and virtual servers are managed to support university services, such as email, learning management system, web site, virtual applications, databases, etc.

Management of the complex WPI network, provides these services:

- High speed fiber optic network connects campus buildings including residence halls
- Pervasive wireless network throughout all campus buildings and many outdoor spaces
- High speed internet connectivity including connection to Internet2
- Virtual Private Network (VPN) access enables secure remote connection to WPI on-campus information technology resources

Enterprise Systems

Banner and the other enterprise wide technology solutions are managed to enable administrative departments to run the critical business functions of the university. These systems provide students and faculty access to important student registration, advising, and financial information. They also enable students to update their biographical information, manage course registration, and check grades online.

Gordon Library

The George C. Gordon Library is open over one hundred hours each week during the academic year. The library provides resources and innovative services in support of the teaching, learning and scholarship process at WPI.

The library's collections support the curriculum and research needs of the WPI community. Currently the library holds thousands of print and electronic journals, a vast collection of electronic books, print books, and research databases which support all areas of the WPI curriculum. The library collection also contains undergraduate project reports, graduate theses and dissertations, with recent years available online. Music CDs, DVDs and other media, and bestsellers are available for educational and recreational purposes. The Library's Curation, Preservation, and Archives department includes the historic records and artifacts of the university and a growing collection that features the inventions of WPI alumni.

The library catalog, electronic journal and book collections, specialized research databases, course-specific information, and many other resources are available from the library's website (http://www.wpi.edu/+library). The website is the focal point for digital library resources and services. Access to WPI users who are off-campus is available through the proxy server.

The staff of Gordon Library offer many services that support graduate students. The Research and Instruction Librarians help students with research problems and questions, offer library instruction and orientation sessions, and provide research consultations to individual graduate students and to groups. Students can request materials not held in Gordon Library through the interlibrary loan service. WPI students also have access to the collections of other academic libraries within Central Massachusetts with the library's membership in the Academic and Research Collaborative (ARC). Students can obtain an ARC cross-borrowing card which allows direct borrowing at many regional academic libraries.

The Gordon Library, Academic Technology Center, and the Technology Service Desk provide one stop shopping for graduate student research, information, and technology support in the Information Commons on the library's main floor. The adjacent Class of 1970 Library Café serves food and beverages.

The library's four floors contain a wide variety of individual and group study spaces. Tech Suites, which are collaborative work areas equipped with up-to-date technology, can be reserved for student use. Additional group study spaces are located throughout the building. There are also computer workstations configured for group and individual use, many with large monitors for collaborative project work. The Multimedia Lab on the first floor offers specialized multimedia software. The Anderson Instruction Labs are used by staff for training during the day and can be used by student groups evenings and weekends. The library features both wireless and wired computer network access, and over 125 public-use computers. Special exhibits are offered regularly in the library's galleries. For more information please visit the library website at http://www.wpi.edu/+library.

Housing

Most graduate students live in rooms or apartments in residential areas near the campus. A limited amount of on-campus housing may be available for single graduate students. Family housing is not available on campus.

The Office of Residential Services, 508-831-5645, provides information regarding both on-campus and off-campus housing. A listing of off-campus accommodations is available at www.wpi.edu/Admin/RSO/Offcampus/.

International Graduate Student Services

The Office of International Students and Scholars is located at WPI's International House at 28 Trowbridge Road. The office provides information and assistance on immigration and other regulatory matters, information on cultural and social programs and services, as well as general counseling.

With 1,472 international students from 85 countries (Fall semester, 2015), WPI is the embodiment of the diversity that characterizes the United States. The House serves as a venue for a variety of programs throughout the year, such as coffee hours, movies, Midnight Breakfast, lectures and other social and cultural activities. The House, which provides wireless access to the network, has several facilities available to students and scholars and student groups interested in international issues, including:

- International Seminar Room for discussion groups, meetings and ESL classes
- International Resources Room with cross-cultural material, travel information and ESL materials as well as computer access
- lounge for students and visitors to relax and enjoy a cup of coffee or a game of backgammon
- two guest rooms for temporary housing

Office of International Students and Scholars: 508-831-6030. ESL Director: 508-831-6033.

Mail Services

Located in the Campus Center, first floor. Student Mail Room 508-831-5317, Incoming/Receiving 508-831-5523, Mail Processing 508-831-5317.

- Package pick-up
- Stamps sold
- Letters and packages weighed, metered
- Discounted Express Mail
- Fax services
- Limited number of mailboxes available

Printing Services

Located in Boynton Hall, lower level. Telephone 508-831-5842 or -5571. Hours (Monday through Friday) 8 a.m. to 4:30 p.m.

- Offset printing
- Photocopying (including color)
- Binding of reports
- Laminating
- Print from disc, electronically sent files or hard copy

Sports and Recreation

The university provides a varied program of sports and recreation. Graduate students usually enter teams in several intramural sports and may participate in certain intercollegiate club sports as well as on-campus musical or theater groups.

The NEW Sports and Recreation Center presents an opportunity for the whole WPI community to be more active and practice healthier lifestyles.

The Sports and Recreation facilities includes a two-story fitness center with cardio equipment and free weights, a four-court gymnasium, a competition pool, dance studios, a three-lane jogging track, racquetball and squash courts. Graduate students frequently join faculty groups for noontime jogging, aerobics and basketball.

A wide variety of entertainment is brought to the campus, ranging from small informal groups to popular entertainers in the 3,500-seat Harrington Auditorium. A series of films is shown in Perreault Hall, and chamber concerts are presented in the Baronial Hall of Higgins House.

The normal social activities of a medium-sized city are readily accessible, many within easy walking distance. Other activities of interest to students are offered by the many colleges in the Worcester Consortium.

Student ID Cards

The WPI ID is also a student's library card and is used in many departments for lab access as well.

Students may also deposit money on their cards for use in the WPI dining locations at a 10% discount. The ID office is located in East Hall. The hours are: Monday through Friday 8 a.m. to 5 p.m. For information, call 508-831-5150.

Dean of Graduate Studies

The Dean of Graduate Studies is the principal advocate for graduate programs across all disciplines at WPI. Graduate students needing assistance with academic issues should reach out to the Dean's Office. The Dean manages offers of funding for graduate Teaching Assistants (TAs), Research Assistants (RAs), and graduate fellowships, oversees the distribution of graduate TAs, coordinates the annual graduate student orientations, and other major events for graduate students, including Graduate Research Innovation Exchange, the i3 Competition, the Fellowship Recognition Dinner, Student Training and Readiness Sessions (STARS), the Graduate Student Travel Fund, the PhD Global Research Experience, and other graduate student professional development activities. In addition, the Dean serves as the chief academic advisor to the Graduate Student Government.

Dean of Students

The Dean of Students' office staff is available to students enrolled in all programs to assist with any out-of-the-classroom concerns that may arise. Staff members are available between 8:30 a.m. and 5 p.m. Appointments outside of these hours can be arranged by calling 508-831-5201.

Aerospace Engineering

Core Faculty

Nikolaos A. Gatsonis, Professor and Program Director; Ph.D., Massachusetts Institute of Technology. Continuum and atomistic computational methods for fluids and plasmas, development of plasma diagnostics and microfluidic devices, spacecraft propulsion and micropropulsion, spacecraft/environment interactions.

John J. Blandino, Associate Professor and Chair of Undergraduate Committee; Ph.D., California Institute of Technology. Fluid mechanics and heat transfer in microdevices, plasma diagnostics, electric and chemical propulsion, propulsion system design for precision formation flying.

Raghvendra Cowlagi, Assistant Professor; Ph.D., Georgia Institute of Technology. Autonomous mobile vehicles, motion planning and optimal control, hybrid optimal control with applications in aerospace engineering, formal methods for system safety and reliability.

Michael A. Demetriou, Professor and Chair of Graduate Committee; Ph.D., University of Southern California. Control of intelligent systems, control of fluid-structure interaction systems, fault detection and accommodation of dynamical systems, acoustic and vibration control, smart materials and structures, sensor and actuator networks in distributed processes, spacecraft attitude estimation and control.

Nikhil Karanjgaokar, Ph.D., University of Illinois at Urbana-Champaign: Experimental mechanics at micro/nano-scale, temperature and rate dependent mechanics of nanostructured materials, dynamic response and flow of granular media, mechanics and damage of inhomogeneous materials, optical measurement techniques.

David J. Olinger, Associate Professor, Ph.D., Yale University. Fluid mechanics, aero and hydrodynamics, fluid structure interactions, fluid flow control, renewable energy.

Mark W. Richman, Associate Professor, Ph.D., Cornell University. Mechanics of granular flows, powder compaction, powder metallurgy.

Affiliated Faculty

Diana Lados, Associate Professor; Ph.D., Worcester Polytechnic Institute. Design and optimization of materials for fatigue, fatigue crack growth, and fracture resistance, fracture mechanics, residual stress, plasticity, solidification.

Ali Rangwala, Professor; Ph.D., University of California, San Diego. Combustion, flame spread on solid fuels and compartment fire modeling, dust explosions.

Richard D. Sisson, Jr., George F. Fuller Professor; Ph.D., Purdue University. Materials process modeling and control, manufacturing engineering, corrosion, environmental effects on metals and ceramics.

Jamal Yagoobi, George Alden Professor, Ph.D., University of Illinois Urbana Champaign. Heat transfer in macro, micro and nano-scales, liquid vapor phase change, electrohydrodynamics, impinging jets.

Programs of Study

The Aerospace Engineering offers three graduate programs of study with the following degree options:

- The Master of Science (M.S.) program leading to the M.S. degree.
- The combined Bachelor of Science (B.S.)/Master of Science Program leading to the B.S. and M.S. degrees.
- The Doctor of Philosophy (Ph.D.) program leading to the Ph.D. degree.

Admission Requirements

For the M.S. program, applicants should have a B.S. in aerospace engineering or in a related field (i.e., other engineering disciplines, physics, mathematics, etc.). The requirements are the same for admission into the thesis and non-thesis options of the M.S. program. At the time of application to the master's program, the student must specify his/her thesis option (thesis or non-thesis).

For the combined B.S./M.S. program, students must be currently enrolled as WPI undergraduates in aerospace engineering or in a related engineering field. When applying to the B.S./M.S. program, students must specify their intention to pursue either the thesis or non-thesis M.S. option.

For the Ph.D. program, a B.S. or M.S. degree in aerospace engineering or in a related field (i.e., other engineering disciplines, physics, mathematics, etc.) is required. The Aerospace Engineering Program reserves its financial aid for graduate students in the Ph.D. program or in the thesis option of the M.S. program.

Degree Requirements

The AE degrees are based on a graduate curriculum which is composed of three areas of study: Fluids and Propulsion; Materials and Structures; Dynamics and Controls. Each area of study consists of a Core and Breadth component as shown in Table 1.

Table 1: Core and Breadth Areas of Study in AE

Fluids and Propulsion

Core

AE 5101/ME 5101. Fluid Dynamics (2 credits) or

AE 5107/ME 5107. Applied Fluid Dynamics

AE 5106. Air Breathing Propulsion (2 credits) or

AE 5111. Spacecraft Propulsion (2 credits)

Breadth

AE 5102. Advanced Gas Dynamics (2 credits)

AE 5104/ME 5104. Turbomachinery (2 credits)

AE 5105/ME 5105. Renewable Energy (2 credits)

AE 5108/ME 5108. Introduction to Computational Fluid Dynamics

AE 5110. Introduction to Plasma Dynamics (2 credits)

AE 6108/ME 6108. Intermediate Computational Fluid Dynamics (2 credits)

Dynamics and Control

Core

AE 5223. Space Vehicle Dynamics and Control (2 credits) or

AE 5224. Air Vehicle Dynamics and Control (2 credits)

AE 5220/ME 5220. Control of Linear Dynamical Systems (2 credits)

Breadth

ME 5200. Mechanical Vibrations (2 credits)

ME 5202. Advanced Dynamics (2 credits)

AE 5221/ME 5221. Control of Nonlinear Dynamical Systems (2 credits)

AE 5222. Optimal Control of Dynamical Systems (2 credits)

Materials and Structures

Core

AE 5383. Composite Materials (2 credits)

AE 5380/ME 5380. Foundations of Elasticity (2 credits) or

AE 5381/ME 5381. Applied Elasticity (2 credits)

Breadth

AE 5382. Aeroelasticity (2 credits)

ME 5303/CE 5303. Applied Finite Element Methods in Engineering (2 credits)

ME 5311/MTE 511. Structure and Properties of Engineering Materials (2 credits)

ME 5312/MTE 512. Properties and Performance of Engineering Materials (2 credits)

M.S. Degree

When applying to the Master of Science degree, students must specify their intention to pursue either the thesis or non-thesis M.S. option. Both the thesis and non-thesis options require the completion of 30 graduate credit hours. Students in the thesis option must complete 12 credits of thesis research (AE 5099), whereas students in the non-thesis option may complete up to 8 credits of directed research (AE 5098). The result of the research credits (AE 5098) in the thesis option must be a completed master's thesis. The number of directed research credits (AE 5098) completed in the non-thesis option can range from 0 to 8.

In the thesis option, the distribution of credits is as follows:

- 6 graduate credits, with 2 credits in each of the three AE Core Areas of Study
- 12 graduate credits of thesis research (AE 5099)
- 8 graduate credits of free electives in or outside AE
- 4 graduate credits in applied mathematics (ME 5000, ME 5001, or any other course with the approval of the AE Graduate Committee)

In the non-thesis option, the distribution of credits is as follows:

- 18 graduate credits in AE courses, with a minimum of 2 credits in each of the three AE Core Areas of Study (includes a maximum of 8 credits of directed research – AE 5098)
- 8 graduate credits of free electives in or outside AE
- 4 graduate credits in applied mathematics (ME 5000, ME 5001, or any other course with the approval of the AE Graduate Committee)

In either option, all students are required to register for the zero-credit Graduate Aerospace Engineering Colloquium (AE 5090), for a minimum of two terms.

Academic Advising

The schedule of academic advising ensures that students are well advised throughout the program.

Temporary Advisor: upon admission to the M.S. program (thesis or non-thesis), each student is assigned or may select a Temporary Advisor. Arranges an academic plan covering the first 8 credits of prior to the first registration.

Academic Advisor: elected by a student prior to registering for more than 8 credits. Arranges an academic plan covering the remaining course of study.

Thesis Advisor (for thesis option students): elected by a student prior to registering for more than 8 credits. Arranges the thesis topic and the academic plan covering the remaining course of study.

Thesis Defense

Each student in the thesis option must defend his/her research during an oral defense, which is administered by the Thesis Advisor and a representative of the AE Graduate Committee. The defense is open to public participation and consists of a 30-minute presentation by the student followed by a 30-minute open discussion. At least one week prior to the defense the Thesis Advisor and an AE Graduate Committee Representative must receive a copy of the thesis. Public notification of the defense must be given by the AE program office. The Thesis Advisor will determine the acceptability of the student's thesis and will determine the student's grade.

Changing M.S. Options

Students in the non-thesis M.S. option may switch into the thesis option at any time by notifying the AE Graduate Committee of the change, provided that they have identified a Thesis Advisor and have worked out a Plan of Study with their thesis advisor. Subject to the Thesis Advisor's approval, directed research credits (AE 5098) earned in the non-thesis option may be transferred to thesis research credits (AE 5099) in the thesis option.

Any student in the thesis M.S. option may request a switch into the non-thesis option by submitting the request in writing to the AE Graduate Committee. Before acting on such a request, the Graduate Committee will require and seriously consider written input from the student's Thesis Advisor. Financial aid given to the thesis-option students who are permitted to switch to the non-thesis option will automatically be withdrawn. Subject to the approval of the AE Graduate Committee, a maximum of 9 credits of thesis research (AE 5099) earned by a student in the thesis option may be transferred to directed research credit (AE 5098) in the non-thesis option.

The Combined B.S./M.S. Program

The AE Program offers a combined B.S./M.S. program for currently enrolled WPI undergraduates. When applying to the B.S./M.S. program, students must specify their intention to pursue either the thesis or non-thesis M.S. option. Both the thesis and non-thesis options require the completion of 30 graduate credit hours.

For students admitted in the B.S./M.S. program, a maximum of 8 graduate credits may be counted toward both the undergraduate and graduate degrees. Double-counted graduate credits must be in courses, including graduate-level independent study and special topics. A maximum of four (4) credits can be double-counted in courses from Engineering, Basic Science or Mathematics which must be at the 4000-level. A grade of B or better is required for any course to be counted toward both degrees.

Acceptance into the B.S./M.S. program means that the candidate is qualified for graduate school, and signifies approval of the graduate courses listed for credit toward both the undergraduate and graduate degrees.

Students in the B.S./M.S. program who choose the thesis M.S. option are encouraged to pick a thesis area of research that is closely related to the subject of their major qualifying project. Those students in the B.S./M.S. program who complete their B.S. degrees in May and choose the thesis option are encouraged to begin their thesis research during the summer immediately following graduation.

Ph.D. Degree

The course of study leading to the Ph.D. degree in aerospace engineering requires the completion of 90 credits beyond the bachelor's degree, or 60 credits beyond the master's degree.

For students proceeding directly from B.S. degree to Ph.D. degree, the 90 credits should be distributed as follows:

- 30 graduate credits in coursework
  - 16 graduate credits in AE courses (incl. Special Topics and ISP)
  - 10 graduate credits in courses in or outside of AE
  - 4 graduate credits in applied mathematics (ME 5000, ME 5001, or any other course with the approval of the AE Graduate Committee)
- 30 graduate credits in Dissertation Research (AE 6099)
- 30 graduate credits in
  - Additional coursework
  - Additional Dissertation Research (AE 6099)
  - Supplemental Research (AE 5098, AE 6098)

TOTAL 90 credits

For students proceeding from Master's to Ph.D. degree, the 60 credits should be distributed as follows:

- 12 graduate credits in AE courses (incl. Special Topics and ISP)
- 30 graduate credits in Dissertation Research (AE 6099)
- 18 graduate credits in
  - courses in or outside of AE
  - Dissertation Research (AE 6099)
  - Supplemental Research (AE 5098, AE 6098)

TOTAL 60 credits

In either case, the result of the dissertation research must be a completed doctoral dissertation. Only after admission to Candidacy may a student receive credit toward Dissertation Research under AE 6099. Prior to admission to Candidacy, a student may receive up to 18 credits of pre-dissertation research under AE 6098. All full-time students are required to register every term for the zero-credit Graduate Aerospace Engineering Colloquium (AE 5090).

Academic Advising and Schedule

The schedule below ensures that students are well advised and actively engaged in their research at all stages of their programs.

- Temporary Advisor: upon admission to the Doctoral Program, each student is assigned or may select a temporary advisor to arrange an academic plan covering the first 8-10 credits of study. This plan should be arranged before the first day of registration.
- Dissertation Advisor: agreed upon by faculty and student prior to registering for more than 8-10 credits.
- Plan of Study and Dissertation Topic: approved by the Dissertation Advisor prior to registering for more than 8-10 credits.
- Admission to Candidacy: Admission to candidacy will be granted after the student has satisfactorily passed a written Qualifying Exam.
- Dissertation Committee: formed prior to registering for more than 18 credits and after admission to Candidacy. The Dissertation Committee consists of the Dissertation Advisor, at least one core faculty of the Aerospace Engineering Program, and at least one outside member.
- Dissertation Proposal: presented by a Doctoral Candidate to the Dissertation Advisor and at least one member of the Dissertation Committee prior to registering for more than 18 credits.
- Dissertation Defense: presented orally by the Doctoral Candidate to the Dissertation Committee and an AE Graduate Committee Representative.

Admission to Candidacy

Admission to candidacy will be granted when the student has satisfactorily passed a written Qualifying Exam intended to measure fundamental ability in the three Core Areas of Study: fluids and propulsion; dynamics and control; materials and structures. The Qualifying Exam is given in the first week of D term and, if required, a Retake Qualifying Exam is given in the middle of D Term. For full-time students who enter the program in the fall the exam must be taken after three terms and after five terms if they began in the spring. The Qualifying Exam is graded using a Pass/Fail system with Pass/Fail grading in each of the three Core Areas of Study. A student must earn a Pass in all three Core Areas of Study in order to earn a Pass in the Qualifying Exam. A student may attempt the Retake Qualifying Exam for the Core Areas of Study failed during the Qualifying Exam. If a student fails to earn a Pass in all three Core Areas of Study of the Qualifying Exam and the Retake Qualifying Exam, he/she must withdraw from the Ph.D. program by end of D term of the year of the Exam. The details of the examination procedure can be obtained from the Aerospace Engineering Office.

Dissertation Proposal

Each Doctoral Candidate must prepare a brief written proposal and make an oral presentation that demonstrates a sound understanding of the dissertation topic, the relevant literature, the techniques to be employed, the issues to be addressed, and the work done on the topic by the student to date. The Dissertation Proposal must be made within a year after the Qualifying Exam and admission to candidacy. Both the written and oral parts of the Proposals are presented to members of the Dissertation Committee and a representative from the AE Graduate Committee. The prepared portion of the oral presentation should not exceed 40 minutes, and up to 60 minutes should be allowed for discussion. If the members

of the Dissertation Committee and the Graduate Committee representative have concerns about either the substance of the proposal or the student's understanding of the topic, then the student will have one month to prepare a second presentation that focuses on the areas of concern. This presentation will last 15 minutes with an additional 35 minutes allowed for discussion. Students can continue their research only if the Dissertation Proposal is approved. If the Dissertation Proposal is not approved, the Doctoral Candidate may find a new Dissertation Advisor and proceed with a new Dissertation Proposal.

Dissertation Defense

Each Doctoral Candidate is required to defend the originality, independence and quality of research during an oral dissertation defense that is administered by an examining committee that consists of the Dissertation Committee and a representative of the AE Graduate Committee who is not on the Dissertation Committee. The defense is open to public participation and consists of a one-hour presentation followed by a one-hour open discussion. At least one week prior to the defense, each member of the examining committee must receive a copy of the dissertation. At the same time, an additional copy must be made available for members of the WPI community wishing to read the dissertation prior to the defense, and public notification of the defense must be given by the aerospace engineering graduate program secretary. The examining committee will determine the acceptability of the student's dissertation and oral performance. The dissertation advisor will determine the student's grade.

Laboratories and Facilities

Aerospace Engineering MQP Laboratory

HL005 (AE Faculty)

This 450 sq. ft. facility supports Major Qualifying Project work associated with a number of different aerospace related projects. Workbenches provide the space required for assembly, integration, and testing of hardware, often with more than one student group working together on complex, interrelated projects.

Aerodynamics Test Facility

HL016 (Olinger, Linn)

This 975 sq. ft. laboratory houses a low-speed, closed-return wind tunnel, with a test-section of 2′′2′′8'. The tunnel speed is continuously variable up to 180 ft/s. The temperature in the tunnel can be controlled via a controller and a heat exchanger in the settling chamber. The tunnel is equipped with a two-component dynamometer. Aerodynamic flows are studied in this laboratory with the aid of traditional pressure, temperature, and velocity sensors, as well as advanced optical instrumentation. The test facility is used for graduate research and undergraduate projects.

Laboratory for Fluids and Plasmas

HL016, HL313 and HL314 (Blandino, Gatsonis)

The Laboratory for Fluids and Plasmas (LFP) supports research and educational activities in electric and chemical micropropulsion, plasma diagnostics, and microfluidics.

The LFP-016 covers 450 sq. ft and houses a 50 inch diameter, 72 inch long stainless steel vacuum chamber (T2), which enables the characterization of electric and chemical thruster component performance. The pumping system for T2 includes a rotary mechanical pump, positive displacement blower combination capable of providing substantial pumping speed (> 560 liters/sec) at low vacuum (10^{-2} - 10^{-3} torr). This pump pair can be used for tests requiring relatively high mass flow rates, such as plume measurements on micro-chemical thrusters. For tests of electric thrusters where lower pressures (higher vacuum) are required, a 20 inch cryopump is available which can provide up to 10,000 liters/s (on N_2) at pressures in the low 10^{-6} torr range. A second, medium-sized vacuum chamber (T4), consists of a 29.75 inch diameter, 34.25 inch tall stainless steel bell-jar. T4 uses a Leybold TurboVac 361 turbomolecular pump backed by a Leybold Trivac D16B rotary-vane dual-stage mechanical pump. The turbopump is rated for a pump speed of 350 L/s on air at pressures in the low 10^{-6} torr range. Both T2 and T4 are equipped with multiple ports for electrical and optical access. The LFP is also equipped with a variety of ancillary instrumentation including power supplies and oscilloscopes as well as data acquisition and flow delivery hardware.

The LFP in HL313-314 covers 600 sq. ft. It houses two vacuum chambers and specialized test facilities for the investigation of onboard micropropulsion, electrospray sources (for both propulsion and nano-fabrication applications), plume/spacecraft interactions, microsensors, and microfluidics. The first chamber (T1) is an 18 inch diameter, 30 inch tall stainless steel bell-jar equipped with a 6 inch diffusion pump backed by a 17 cfm mechanical pump. The system is capable of an ultimate pressure in the low 10^{-6} torr range. The second vacuum chamber (T3), is a 22.5 inch diameter, 32 inch tall stainless steel bell-jar. It is equipped with a 6-inch diffusion pump backed by a Varian DS 602 dual stage rotary vane pump. The system is capable of achieving an ultimate pressure in the 10^{-6} torr range. T3 also includes a computer controlled probe positioning system. The system consists of micos linear (VT-80) and rotary (DT-80) computer-controlled stages to achieve precise, three degree-of-freedom positioning. In addition, T3 is equipped with a 3-centimeter Kauffman Ion Source with computer-controlled, mass flow delivery. For microfluidics research, the LFP includes equipment for studies of two-phase flows in microchannels. Imaging equipment for these flows includes a high-resolution monochrome progressive scan Pulnix-1325 camera with computer based image-capture and processing software. In addition, a portable fume hood work space is available for use in testing of dielectrophoretic flows with high vapor-pressure fluids. The LFP-314/313 includes a variety of tools and specialized instrumentation including a syringe pump, oscilloscopes, precision source meter, electrometer, and digital multimeters. Data from these instruments can be collected and stored on computer using a LabView based data acquisition system.

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Computational Fluids and Plasmas Laboratory

HL236 (Gatsonis)

This is a 660 sq. ft. modern computational facility used for graduate research and educational activities in computational methods and their applications to fluids, gases and plasmas. CFPL pursues also multidisciplinary collaborative projects involving controls and dynamics. The CFPLL includes workstations and a Linux cluster located in HL231, a specially designed computer facility. The CAL has access to Direct Simulation Monte Carlo, Particle-in-Cell, fluid dynamics, and MHD codes as well as visualization and data reduction software.

Fluid Dynamics Laboratory

HL311 (Olinger)

This 420 sq. ft. laboratory is used for research and educational activities in fluid dynamics. It houses a low speed, low turbulence wind tunnel facility with a one-foot square test section which is used for experiments on low Reynolds number aerodynamics related to biologically inspired flight, and fluid-structure interaction. These systems are of practical importance in many aero- and hydrodynamic systems, such as micro-air vehicles and flow-induced vibration of flexible cables Standard equipment such as vibration shakers, hot-wire anemometry systems, spectral analyzers, digital oscilloscopes and data acquisition systems are also used in the laboratory.

Gasdynamics and Propulsion Laboratory

HL311 (Im)

The Gasdynamics and Propulsion Laboratory (GPL) is used for research and educational activities in gasdynamics and air-breathing propulsion research areas. It is equipped with high speed imaging, laser based diagnostics, optical spectroscopy, and gas analyzing systems. High speed imaging and diagnostics allow visualization and measurements of transient flow phenomena in compressible flows and chemically reacting flows.

Structures and Materials Laboratory

HL028 (Karanjgaokar)

The structures and material laboratory is used for undergraduate and graduate research in field of mechanics of novel materials and structures used in aerospace systems. The laboratory is equipped with NI Compact DAQ acquisition system for actuation and sensing applications to understand the mechanics of structures and materials. The laboratory includes an optical microscopy suite to visualize the full-field deformation of nanostructured materials with nanoscale resolution using Digital Image Correlation (DIC). The laboratory also hosts a high speed imaging system to investigate the mechanics of granular media under dynamic loading and the flow of granular media. The laboratory also focusses on the dynamic response of granular media and inhomogeneous materials using a gas-gun based impact testing setup. The laboratory is equipped with a Laser Scanning Doppler Vibrometer system to measure the velocity of vibrations in structures like particle dampers and ferroelectrics in low and high frequency ranges.

Systems and Robot Control Laboratory

HL312 (Demetriou, Cowlagi)

The Systems and Robot Control Laboratory (SRCL) is a 600 sq. ft. facility equipped for experiments in control of unmanned aerial vehicles, wheeled robots, submersible vehicles, and dynamical systems with flexible structures. Workbenches equipped with power supplies, amplifiers, signal generators, data acquisition systems, and oscilloscopes are provided. For experiments in robot autonomy, state-of-the-art microcontroller platforms, such as the Raspberry Pi 2, along with sundry electronic components are available for rapid prototyping and implementation of onboard vehicle control systems. A variety of off-the-shelf radio-controlled vehicle platforms are available, including a series of Align T-REX single-rotor helicopters, the IRIS and Spiri quadrotor helicopters, and iRobot Create wheeled robots. For experiments in control and optimization of flexible structures, an active vibration isolation table, velocity sensors, accelerometers, piezoceramic patches for actuation and sensing and a dSPACE® ACE1103 real-time data acquisition and control package are available.

Aerodynamics Integration and Calibration Laboratory

HL305 (Linn)

This 120 sq ft. laboratory is a integration, calibration and staging area for wind tunnel test rigs and other experimental apparatus. Within this laboratory experimental apparatus is assembled, instrumented and tested prior to installation in one of the Aerospace Engineering tunnel facilities or flight test.

Aerospace Engineering Discovery Classroom

HL216 (AE Faculty)

In the Discovery Classroom, the traditional lecture hall is redefined to combine a multi-media classroom and an adjoining experimental 570 sq. ft. laboratory. The capabilities of the classroom allow us to use an integrated analytical – numerical – experimental approach to aerospace engineering in fludis, propulsion, materials and structures courses. We have designated the approach using this facility as the DIANE philosophy: **D**aily **I**ntegration of **A**nalytical, **N**umerical, and **E**xperimental methods into aerospace engineering classes. In a typical application, experimental apparatus are demonstrated directly in class during an engineering lecture. Real-time quantitative data are acquired from the apparatus, and the data are analyzed and compared to concurrently developed theory by the students in class. The lab includes a portable wind tunnel, a portable water tunnel, a buckling apparatus, a shear center apparatus and various other setups.

Course Descriptions

All courses are 3 credits unless otherwise noted.

Fluids and Propulsion

AE/ME 5101. Fluid Dynamics

(2 credits)

This course presents the following fundamental topics in fluid dynamics: concept of continuum in fluids; kinematics and deformation for Newtonian fluids; the mass conservation equation, momentum and energy equations for material volumes and control volumes; the differential form of mass conservation, momentum and energy equations. This course covers also applied topics chosen from: unidirectional steady incompressible viscous flows; unidirectional transient incompressible viscous flows; lubrication flows similarity and dimensional analysis. This is an introductory graduate-level course and may be taken independent of AE 5107/ME 5107.

AE 5102. Advanced Gas Dynamics
(2 credits)
An introduction to kinetic theory of gases and its application to equilibrium flows and flows with chemical, vibrational and translational nonequilibrium. Topics in kinetic theory also include the Boltzmann Equation and its relation to the continuum equations of gas dynamics. A major focus of the course is exploring how results for equilibrium flow of a perfect gas (e.g. flows in nozzles, normal and oblique shocks, expansion waves) are modified for an imperfect gas with nonequilibrium. The models of flow with nonequilibrium are then applied to the study of different flows of engineering interest including hypersonic flows (e.g. re-entry vehicles), propagating shock waves (explosions), and chemically reacting flows. Students cannot receive credit for this course if they have taken the Special Topics (ME 593G) version of the same course or ME 512.

AE/ME 5104. Turbomachinery
(2 credits)
This course is an introduction to the fluid mechanics and thermodynamics of turbomachinery for propulsion and power generation applications. Axial and centrifugal compressors will be discussed as well as axial and radial flow turbines. Analysis of the mean line flow in compressor and turbine blade rows and stages will be discussed. The blade-to-blade flow model will be presented and axisymmetric flow theory introduced. Three-dimensional flow, i.e. secondary flows, will also be discussed. Students cannot receive credit for this course if they have taken the Special Topics (ME 593H) version of the same course.

AE/ME 5105. Renewable Energy
(2 credits)
The course provides an introduction to renewable energy, outlining the challenges in meeting the energy needs of humanity and exploring possible solutions in some detail. Specific topics include: use of energy and the correlation of energy use with the prosperity of nations; historical energy usage and future energy needs; engineering economics; electricity generation from the wind; wave/ocean energy, geo-thermal and solar-thermal energy; overview of fuel cells, biofuels, nuclear energy, and solar-photovoltaic systems and their role and prospects; distribution of energy and the energy infrastructure; energy for transportation; energy storage. Pre-requisites; ES 3001, ES 3004 or equivalents. Students cannot receive credit for this course if they have taken the Special Topics (ME 593R) version of the same course.

AE 5106. Air Breathing Propulsion
(2 credits)
This course covers at the introductory graduate level the design and performance of air-breathing propulsion engines. Topics covered will be chosen from: jet propulsion theory, gas turbine, ramjet, scramjet, gas dynamics of inlet and nozzle flows, component matching, thermodynamic cycle analysis of the propulsion systems, and combustion control in propulsion systems.

AE/ME 5107. Applied Fluid Dynamics
(2 credits)
This course presents applications of incompressible and compressible fluid dynamics at an introductory graduate level. Topics are chosen from: potential flows; boundary layers; vorticity dynamics and rotating flows; aerodynamics; introduction to turbulence; micro/nano flows. This course can be taken independent of AE 5101/ME 5101.

AE/ME 5108. Introduction to Computational Fluid Dynamics
(2 credits)
The course provides the theory and practice of computational fluid dynamics at an entry graduate level. Topics covered include: classification of partial differential equations (PDEs) in fluid dynamics and characteristics; finite difference schemes on structured grids; temporal discretization schemes; consistency, stability and error analysis of finite difference schemes; explicit and implicit finite differencing schemes for 2D and 3D linear hyperbolic, parabolic, elliptic, and non-linear PDEs in fluid dynamics; direct and iterative solution methods for algebraic systems. The course requires completion of several projects using MATLAB.

AE 5110. Introduction to Plasma Dynamics
(2 Credits)
The course introduces concepts of partially ionized gases (plasmas) and their role in a wide range of science and engineering fields. Fundamental theory includes topics in: equilibrium of ionized gases and kinetic theory; motion of charged particles in electromagnetic fields; elastic and inelastic collisions, cross sections and transport processes; fluid theory and magnetohydrodynamic models; sheaths. Applications cover areas such as plasma diagnostics, plasma discharges, spacecraft/environment interactions, and plasma-aided material processing.

AE 5111. Spacecraft Propulsion
(2 Credits)
This course provides students with the background and theory needed to evaluate the performance of the most commonly used electric and chemical spacecraft propulsion systems. Electrostatic ion and Hall thruster theory, design, and operation are covered including theory and operation of hollow cathodes, plasma generation and ion acceleration (including design of ion optics), magnetic field design, and beam neutralization. Topics in chemical propulsion include bipropellant and monopropellant chemistry (adiabatic flame temperature and ideal performance) with a focus on catalyst-bed and nozzle design considerations. Discussion of each class of thruster will be supplemented with specific examples of flight hardware.

AE/ME 6108. Intermediate Computational Fluid Dynamics
(2 credits)
The course presents computational methods for incompressible and compressible viscous flows at an intermediate level. Topics are chosen from: grid generation techniques; finite volume schemes; stability analysis; artificial viscosity; explicit and implicit schemes; flux-vector splitting; monotonic advection schemes; multigrid methods; particle-based simulation methods. (Prerequisite: fluid dynamics; an introductory course in numerical methods for partial differential equations; programming language experience) Students who have received credit for AE/ME 5103 will not receive credit for AE/ME 6108.

Dynamics and Control

AE/ME 5220. Control of Linear Dynamical Systems
(2 credits)
This course covers analysis and synthesis of control laws for linear dynamical systems. Fundamental concepts including canonical representations, the state transition matrix, and the properties of controllability and observability will be discussed. The existence and synthesis of stabilizing feedback control laws using pole placement and linear quadratic optimal control will be discussed. The design of Luenberger observers and Kalman filters will be introduced. Examples pertaining to aerospace engineering, such as stability analysis and augmentation of longitudinal and lateral aircraft dynamics, will be considered. Assignments and term project (if any) will focus on the design, analysis, and implementation of linear control for current engineering problems. The use of Matlab®/Simulink® for analysis and design will be emphasized. (Recommended background: Familiarity with ordinary differential equations, introductory control theory, fundamentals of linear algebra, and the analysis of signals and systems is recommended. Familiarity with Matlab® is strongly recommended.) Students cannot receive credit for this course if they have taken the Special Topics (ME 593N) version of the same course or ME 523.

AE/ME 5221. Control of Nonlinear Dynamical Systems
(2 credits)
Overview of stability concepts and examination of various methods for assessing stability such as linearization and Lyapunov methods. Introduction to various design methods based on linearization, sliding modes, adaptive control, and feedback linearization. Demonstration and performance analysis on engineering systems such as flexible robotic manipulators, mobile robots, spacecraft attitude control and aircraft control systems. Control synthesis and analysis is performed using Matlab®/Simulink®. (Prerequisites: Familiarity with ordinary differential equations, introductory control theory at the undergraduate level, fundamentals of linear algebra. Familiarity with Matlab® is strongly recommended.) Students cannot receive credit for this course if they have taken the Special Topics (ME 593N) version of the same course or ME 623.

AE 5222. Optimal Control of Dynamical Systems
(2 Credits)

This course covers the synthesis of optimal control laws for linear and nonlinear dynamical systems. Necessary conditions for optimal control based on the Pontryagin Minimum Principle will be introduced, and cases of fixed and free terminal time and boundary conditions will be discussed. Feedback optimal control will be discussed, and the Hamilton-Jacobi-Bellman equation will be introduced. The special case of linear quadratic optimal control will be discussed. Examples throughout the course will be based on air- and space vehicle applications, such as flight trajectory optimization. Assignments and term project (if any) will introduce basic numerical techniques, and introduce software packages for optimal control. (Prerequisites: Fluency with the theory of linear dynamical systems and control is required. Familiarity with MATLAB. Familiarity with air- and space vehicle dynamics is beneficial, but not necessary.)

AE 5223. Space Vehicle Dynamics and Control
(2 Credits)

Overview of spacecraft rotational motion. Stability analysis of forced and torque-free spacecraft motion. Effects of space environment and man-made torques on motion stability. Examination of orbital and attitude motion coupling. Theoretical formulation of spacecraft formation flying. Review of current trends in networked miniaturized spacecraft. Overview and sizing of actuating devices such as gas jet, electric thrusters, momentum wheels and magnetic torquers. Overview and selection of sensing devices such as sun sensors, magnetometers, GPS, IMUs. Formulation of spacecraft maneuvers as control design problems. Case studies on feedback attitude regulators and algorithms for linear and nonlinear attitude tracking. Design and realization of attitude control schemes using Matlab®/Simulink®. (Prerequisites: Fundamentals of spacecraft orbital motion and attitude dynamics at the undergraduate level. Familiarity with state space and frequency domain control concepts such as stability, controllability and observability. Familiarity with Lyapunov-based stability analysis of nonlinear dynamical systems. Familiarity with Matlab®.)

AE 5224. Air Vehicle Dynamics and Control
(2 Credits)

This course covers the fundamentals of the dynamics of rigid bodies and their motion under the influence of aerodynamic and gravitational forces. General equations of aircraft motion will be developed, followed by concepts of static and dynamic stability. Trim and linearization will be discussed, and the stability analysis of lateral and longitudinal modes in the linearized equations will be introduced. Stability augmentation via feedback control will be discussed. Aspects of aircraft navigation, guidance, and flight trajectory optimization will also be introduced. (Prerequisites: Familiarity with the kinematics and dynamics of rigid bodies is required. Familiarity with ordinary differential equations is recommended. Familiarity with aircraft dynamics and control at the undergraduate level is beneficial, but not necessary.)

Materials and Structures

ME 5303/CE 5303. Applied Finite Element Methods in Engineering
(2 credits)

This course is devoted to the numerical solution of partial differential equations encountered in engineering sciences. Finite element methods are introduced and developed in a logical progression of complexity. Topics covered include matrix structural analysis variation form of differential equations, Ritz and weighted residual approximations, and development of the discretized domain solution. Techniques are developed in detail for the one- and two-dimensional equilibrium and transient problems. These numerical strategies are used to solve actual problems in heat flow, diffusion, wave propagation, vibrations, fluid mechanics, hydrology and solid mechanics. Weekly computer exercises are required to illustrate the concepts discussed in class. Students cannot receive credit for this course if they have taken the Special Topics (ME 593E) version of the same course or ME 533 or CE 524.

ME 5311/MTE 511. Structure and Properties of Engineering Materials
(2 credits)

This course, (along with its companion course MTE 512 Properties and Performance of Engineering Materials), is designed to provide a comprehensive review of the fundamental principles of Materials Science and Engineering for incoming graduate students. In the first part of this 2-course sequence, the structure in materials ranging from the sub-atomic to the macroscopic including nano, micro and macromolecular structures will be discussed to highlight bonding mechanisms, crystallinity and defect patterns. Representative thermodynamic and kinetic aspects such as diffusion, phase diagrams, nucleation and growth and TTT diagrams will be discussed. Major structural parameters that effect of performance in materials including plastics, metallic alloys, ceramics and glasses will be emphasized. The principal processing techniques to shape materials and the effects of processing on structure will be highlighted. (Prerequisites: senior or graduate standing or consent of the instructor.) Note: Students cannot receive credit for this course if they have taken the Special Topics version of the same course (MTE 594S).

ME 5312/MTE 512. Properties and Performance of Engineering Materials
(2 credits)

The two introductory classes on materials science (MTE511 and MTE512) describe the structure-property relationships in materials. The purpose of this class is to provide a basic knowledge of the principles pertaining to the physical, mechanical and chemical properties of materials. The primary focus of this class will be on mechanical properties. The thermal, tensile, compressive, flexural and shear properties of metallic alloys, ceramics and glasses and plastics will be discussed. Fundamental aspects of fracture mechanics and viscoelasticity will be presented. An overview of dynamic properties such as fatigue, impact and creep will be provided. The relationship between the structural parameters and the preceding mechanical properties will be described. Basic composite theories will be presented to describe fiber-reinforced composites and nanocomposites. Various factors associated with material degradation during use will be discussed. Some introductory definitions of electrical and optical properties will be outlined. (Prerequisites: senior or graduate standing or consent of the instructor.) Note: Students cannot receive credit for this course if they have taken the Special Topics version of the same course (MTE 594P).

AE/ME 5380. Foundations of Elasticity
(2 credits)

This course is suitable as an introductory graduate level course. Topics will be chosen from the following: three-dimensional states of stress; measures of strain; thick-walled cylinders, disks and spheres; plane stress and plane strain; thermoelasticity; Airy stress function; energy methods, and exact theory for torsion of non-circular cross sections. This course may be taken independent of ME 5302. Students cannot receive credit for this course if they have taken the Special Topics (ME 593N) version of the same course or ME 531.

AE/ME 5381. Applied Elasticity
(2 credits)

This course is suitable as an introductory graduate level course. Topics covered will be chosen from the following: bending and shear stresses in unsymmetric beams; bending of composite beams; bending of curved beams; torsion of thin-walled noncircular cross sections; beams on elastic foundations; stress concentrations; failure criteria; stability of columns; and bending of plates. This course may be taken independent of ME 5301. Students cannot receive credit for this course if they have taken the Special Topics (ME 593N) version of the same course or ME 531

AE 5382. Aeroelasticity
(2 credits)
Aeroelastic phenomena arise from the interaction between a fluid and a structure. Such phenomena are encountered in aerospace, mechanical and civil engineering systems. Topics covered include: aeroelastic phenomena in nature, divergence and control effectiveness in static conditions, static and dynamic instabilities of elastic bodies in a flow, flutter of wings, and aeroelastic testing techniques. Students will be introduced to analytical and computational techniques used to model and simulate aeroelasticity. Students cannot receive credit for this course if they have taken the Special Topics (ME 593N) version of the same course.

AE 5383. Composite Materials
(2 credits)
This course covers the anisotropic constitutive behavior and micromechanics of composite materials, and the mechanics of composite structures at an introductory graduate level. Topics covered will be chosen from: classification of composites (reinforcements and matrices), anisotropic elasticity, composite micromechanics, effect of reinforcement on toughness and strength of composites, laminate theory, statics and buckling of laminated beams and plates, statics of laminated shells, residual stresses and thermal effects in laminates.

Other Activities:

AE 5090. Graduate Aerospace Engineering Colloquium
(0 credits)
This pass/fail graduation requirement is intended for graduate students. The Colloquium is offered by an aerospace engineering faculty member once a week, during A, B, C, and D term. Full-time graduate students are required to register every term, attend seminars on technical or broader professional topics, and make presentations on ongoing or previously completed research related to their thesis, dissertation, independent research or industrial experiences. Recommended Background: graduate students in aerospace engineering.

AE 5093. Special Topics
(2 credits)
Arranged by individual faculty with special expertise, these courses survey fundamentals in areas that are not covered by the regular aerospace engineering course offerings. Exact course descriptions are disseminated by the Aerospace Engineering Program in advance of the offering. (Prerequisite: Consent of instructor.)

AE 5098. Directed Research
(credits TBD)
For non-thesis M.S. students wishing to gain research experience, for M.S. students wishing to gain research experience peripheral to their thesis topic, or for Ph.D. students wishing to gain research experience peripheral to their dissertation topic. (Prerequisite: Consent of directed research supervisor.)

AE 5099. Thesis Research
(credits TBD)
For master's students wishing to obtain research credit toward their thesis. (Prerequisite: Consent of thesis advisor.)

AE 6093. Advanced Special Topics
(2 credits)
Arranged by individual faculty with special expertise, these courses cover advanced topics that are not covered by the regular aerospace engineering course offerings. Exact course descriptions are disseminated by the Aerospace Engineering Program in advance of the offering. (Prerequisite: Consent of instructor.)

AE 6098. Pre-Dissertation Research
(credits TBD)
For doctoral students wishing to obtain dissertation-research credit prior to admission to candidacy. (Prerequisite: Consent of dissertation advisor.)

AE 6099. Dissertation Research
(credits TBD)
For doctoral students admitted to candidacy wishing to obtain research credit toward their dissertations. (Prerequisite: Consent of dissertation advisor.)

Bioinformatics and Computational Biology

Faculty with Research Interests

E. F. Ryder, Associate Professor, Biology and Biotechnology, and BCB Program Director; Ph.D., Harvard University, 1993. Computational biology, simulation of biological systems.

L. Harrison, Assistant Professor, Computer Science; Ph.D., UNC-Charlotte, 2013. Information visualization, visual analytics, human-computer interaction.

X. Kong, Assistant Professor, Computer Science; Ph.D., University of Illinois, 2014. Data mining, social networks, machine learning, big data analytics, connectome.

D. Korkin, Associate Professor, Computer Science; Ph.D., University of New Brunswick, Canada, 2003. Bioinformatics of disease, big data in biomedicine, computational genomics, systems biology, data mining, machine learning.

S. D. Olson, Assistant Professor, Mathematical Sciences; Ph.D. North Carolina State University, 2008. Mathematical biology, chemical signaling, mechanics, and hydrodynamics.

R. Paffenroth, Associate Professor, Mathematical Sciences; Ph.D., University of Maryland, 1999. Large scale data analytics, statistical machine learning, compressed sensing, network analysis.

R. Prusty Rao, Associate Professor, Biology and Biotechnology; Ph.D., Penn State University-Medical School. Genomic studies and high throughput screening to understand and manage fungal diseases in humans.

C. Ruiz, Associate Professor, Computer Science; Ph.D., University of Maryland, 1996. Data mining, machine learning, artificial intelligence, biomedical data mining.

B. Servatius, Professor, Mathematical Sciences; Ph.D., Syracuse University, 1987. Combinatorics, matroid and graph theory, structural topology, geometry, history and philosophy of mathematics.

S. Shell, Assistant Professor, Biology and Biotechnology; Ph.D., University of California San Diego. Bacterial pathogenesis, bacterial stress response, prokaryotic gene regulation, prokaryotic genomics and transcriptomics.

E. Tüzel, Associate Professor, Physics; Ph.D., University of Minnesota. Theoretical and computational biophysics, polymer physics, cell mechanics and cargo transport, complex fluids, soft-matter physics.

L. Vidali, Associate Professor, Biology and Biotechnology; Ph.D., University of Massachusetts-Amherst. Plant cell biology and molecular genetics, live cell microscopy, molecular motors/cytoskeleton.

Z. Wu, Associate Professor of Mathematical Sciences, Ph.D., Yale, 2009. Biostatistics, high-dimensional model selection, linear and generalized linear modeling, statistical genetics, bioinformatics.

J. Zou, Assistant Professor; Ph.D., University of Connecticut, 2009. Financial time series (especially high frequency financial data), spatial statistics, biosurveillance, high dimensional statistical inference, Bayesian statistics.

Affiliated Faculty

E.O. Agu (Computer Science); Ph.D., University of Massachusetts-Amherst, 2001. Computer graphics, mobile computing, wireless networks, use of smartphones as a platform to deliver better healthcare.

T. Dominko (Biology and Biotechnology); D.V.M, Ph.D., University of Wisconsin-Madison. Regenerative cell biology, stem cells, role of oxygen and FGF2 in nuclear reprogramming, epigenetics, reproductive/developmental biology.

J. P. Duffy (Biology and Biotechnology); Ph.D., University of Texas. Cancer biology/signal transduction, cancer therapeutics, cell adhesion mechanisms in development and disease, neurobiology and neurodegenerative disorders.

M. Eltabakh (Computer Science); Ph.D., Purdue University, 2010. Database management systems, information management.

A. Manning (Biology and Biotechnology); Ph.D., Geisel School of Medicine at Dartmouth University, 2008. Cancer Cell Biology, cell cycle regulation, mitotic progression and chromosome segregation, chromatin regulation, and genome stability.

W. J. Martin (Mathematical Sciences); Ph.D., University of Waterloo, 1992. Algebraic combinatorics, applied combinatorcs.

S. M. Politz (Biology and Biotechnology); Ph.D., UCLA. Genetic control of surface glycoprotein expression in the nematode C. elegans; chemosensory control of nematode behavior and development; host immune responses to parasitic nematode infections.

E. A. Rundensteiner (Computer Science); Ph.D., University of California, Irvine, 1992. Data and information management, big data analytics, visual data discovery, stream and pattern mining, large scale data infrastructures.

J. Srinivasan (Biology and Biotechnology); Ph.D., University of Tuebingen, Germany. Genetics, behavioral neuroscience, molecular neurobiology, chemical biology, evolutionary ecology.

D. Tang (Mathematical Sciences); Ph.D., University of Wisconsin, 1988. Biofluids, biosolids, blood flow, mathematical modeling, numerical methods, scientific computing, nonlinear analysis, computational fluid dynamics.

Programs of Study

The Bioinformatics and Computational Biology (BCB) Program offers graduate studies toward the B.S./M.S., M.S., and Ph.D. degrees. With the advent of large amounts of biological data stemming from research efforts such as the Human Genome Project, there is a great need for professionals working at the interface of biology, computer science, and mathematics. A truly interdisciplinary program, the BCB degree requires advanced course work in all three of these areas. Our faculty and strong relationships with the University of Massachusetts Medical School

provide students with the resources to perform innovative scientific research at the highest level.

The diverse learning environment that characterizes our program promotes easy exchange of ideas, access to all the necessary resources, and encourages creative solutions to pressing scientific questions.

Admissions Requirements

Students applying to the M.S. or Ph.D. Degree Programs in Bioinformatics and Computational Biology (BCB) are expected to have a bachelor's degree in either biology, computer science, mathematics, or a related field, and to have taken introductory courses in each of the three disciplines: biology, computer science, and mathematics. For example, a student with a bachelor's degree in biology is expected to have also completed courses in programming, data structures, calculus, and statistics prior to submitting an application. A strong applicant who is missing background in one of the three areas may be provisionally admitted, with the expectation that he or she will take and pass one or more undergraduate courses in the area of deficiency either during the summer prior to admission or within the first semester after admission. The determination of what course or courses will satisfy this provision will be made by the Program Review Committee.

Certificate Requirements

A certificate program in BCB is not offered at present.

Degree Requirements

Masters: Students pursuing the M.S. degree in Bioinformatics and Computational Biology must complete a minimum of 33 credits of relevant work at the graduate level. These 33 credits must satisfy the 6-9 credit M.S. thesis or internship requirement, and the 24-27 credit coursework requirement described in detail at the URL below. Coursework requirements include competency in each of the areas of biology, computer science, mathematics, and interdisciplinary studies in bioinformatics / computational biology, as well as more advanced courses and an ethics course. The M.S. degree requirements have been designed to provide a comprehensive yet flexible program to students who are pursuing an M.S. degree exclusively, students who are pursuing a combined B.S./M.S. degree, and students who are pursuing a combined M.S. / Ph.D. degree. Courses and research projects taken at nearby University of Massachusetts Medical School (UMMS) may be applied to this degree. Upon acceptance to the M.S. program, students will be assigned an academic advisor. In consultation with the academic advisor, the student must prepare a Plan of Study outlining the selections that the student will make to satisfy the M.S. degree requirements. This Plan of Study must then be approved by the Program Review Committee, which consists of faculty members from each of the three participating WPI departments.

B.S./M.S.: Students enrolled in the B.S./M.S. program must satisfy all the program requirements of the B.S. degree and all the program requirements of the M.S. degree as described at the URL below. They may double-count 4000-level or graduate courses whose credit hours total no more than 40% of the 33 credit hours required for the M.S. degree, and that meet all other requirements for each degree, towards both their undergraduate and graduate degrees. Students must register for B.S./M.S. credit prior to taking the courses, as faculty may assign extra work for those taking the course as part of both degrees. In consultation with the academic advisor, the student must prepare a Plan of Study outlining the selections that the student will make to satisfy the B.S./M.S. degree requirements, including the courses that the student will double count. This Plan of Study must then be approved by the Program Review Committee. Students must consult their advisors and the graduate catalog, as individual departments may have restrictions on which undergraduate courses might be taken for graduate credit, and on which pairs of undergraduate and graduate courses cannot both be taken for credit.

Ph.D.: Students pursuing the doctoral degree in BCB must complete a minimum of 90 graduate credits of relevant work beyond the bachelor's degree (60 credits if the student possesses a relevant M.S. degree). At least 30 credits must be in dissertation research. Coursework requirements are similar to those for the M.S. degree, with an additional required course in proposal writing. For Ph.D. candidates, presentation of research work is required each year, and there is a teaching / mentorship requirement as well. Students may pursue up to 6 graduate credits as an internship with an external sponsor. Detailed requirements are found at the URL below. Upon acceptance to the program, students will be assigned a temporary academic advisor and prepare a Plan of Study similar to the procedure for M.S. students. Ph.D. students are required to complete rotations with at least two program faculty members in the first year of the program before choosing a research advisor; choosing co-advisors in different disciplines is strongly encouraged. Students are encouraged to consider UMMS faculty for rotations and as co-advisors, and may take UMMS courses to fulfill course requirements.

Qualifying Exam and Dissertation Defense
The Qualifying Examination will be comprised of researching, writing, and defending a research proposal. The student is required to successfully complete the Qualifying Examination no later than the first semester of his/her third year in the program. If the Qualifying Examination is successfully completed, the proposed work may constitute the basis of the student's dissertation research. All Ph.D. students must produce and orally defend a dissertation. The research must constitute a contribution to knowledge in the field of Bioinformatics and Computational Biology and must be of publication quality. Students must defend the dissertation orally in a public presentation, followed by a private defense.

URL for details:
http://www.wpi.edu/+BCB

Facilities/Research Labs/ Research Centers

The BCB Program is supported by a wide assortment of resources within the participating departments, WPI Computing and Communication Center (CCC), and the research laboratories at Gateway Park and UMMS. Grid and cloud computing, along with high-speed networking, provides exceptional computational infrastructure. Access to most major biological databases is available to students and researchers, and a wide range of bioinformatics software packages are installed and maintained. Wet labs at Gateway Park and UMMS are available by permission of BCB faculty members and affiliates.

Course Descriptions

All courses are 3 credits unless otherwise noted.

BCB 501/BB 581. Bioinformatics

This course will provide an overview of bioinformatics, covering a broad selection of the most important techniques used to analyze biological sequence and expression data. Students will acquire a working knowledge of bioinformatics applications through hands-on use of software to ask and answer biological questions. In addition, the course will provide students with an introduction to the theory behind some of the most important algorithms used to analyze sequence data (for example, alignment algorithms and the use of hidden Markov models). Topics covered will include protein and DNA sequence alignments, evolutionary analysis and phylogenetic trees, obtaining protein secondary structure from sequence, and analysis of gene expression including clustering methods. Students may not receive credit for both BCB 4001 and BCB 501. (Prerequisite: knowledge of genetics, molecular biology, and statistics at the undergraduate level.)

BCB 502/CS 582. Biovisualization

This course uses interactive visualization to explore and analyze data, structures, and processes. Topics include the fundamental principles, concepts, and techniques of visualization and how visualization can be used to analyze and communicate data in domains such as biology. Students will be expected to design and implement visualizations to experiment with different visual mappings and data types, and will complete a research oriented project. Prerequisite: experience with programming (especially JavaScript), databases, and data structures. Students may not receive credit for both BCB 502 and BCB 4002.

BCB 503/CS 583. Biological and Biomedical Database Mining

This course will investigate computational techniques for discovering patterns in and across complex biological and biomedical sources, including genomic and proteomic databases, clinical databases, digital libraries of scientific articles, and ontologies. Techniques covered will be drawn from several areas including sequence mining, statistical natural language processing and text mining, and data mining. (Prerequisite: Strong programming skills, an undergraduate or graduate course in algorithms, an undergraduate course in statistics, and one or more undergraduate biology courses.)

BCB 504/MA 584. Statistical Methods in Genetics and Bioinformatics

This course provides students with knowledge and understanding of the applications of statistics in modern genetics and bioinformatics. The course generally covers population genetics, genetic epidemiology, and statistical models in bioinformatics. Specific topics include meiosis modeling, stochastic models for recombination, linkage and association studies (parametric vs. nonparametric models, family-based vs. population-based models) for mapping genes of qualitative and quantitative traits, gene expression data analysis, DNA and protein sequence analysis, and molecular evolution. Statistical approaches include log-likelihood ratio tests, score tests, generalized linear models, EM algorithm, Markov chain Monte Carlo, hidden Markov model, and classification and regression trees. Students may not receive credit for both BCB 4004 and BCB 504. (Prerequisite: knowledge of probability and statistics at the undergraduate level.)

BCB 510. BCB Seminar

This seminar provides an opportunity for students in the BCB program to present their research work, as well as hear research talks from guest speakers. 1 credit per semester.

BCB 590. Special Topics in Bioinformatics and Computational Biology

An offering of this course will cover a topic of current interest in detail. See the Supplement section of the on-line catalog at www.wpi.edu/+gradcat for descriptions of courses to be offered in this academic year. Prerequisites will vary with topic.

BCB 596. Independent Study

This course will allow a student to study a chosen topic in Bioinformatics and Computational Biology under the guidance of a faculty member affiliated with the Bioinformatics and Computational Biology program. The student must produce a written report at the conclusion of the independent study.

BCB 597. Directed Research

Directed research conducted under the guidance of a faculty member affiliated with the BCB Program.

BCB 598. Graduate Internship

A graduate internship is carried out in cooperation with a sponsor or industrial partner. It must be overseen by a faculty member affiliated with the Bioinformatics and Computational Biology Program. The internship will involve development and practice of technical and professional skills and knowledge relevant to Bioinformatics and Computational Biology. At the completion of the internship, the student will produce a written report, and will present their work to BCB faculty and internship sponsors.

BCB 599. M.S. Thesis Research

A Master's thesis in Bioinformatics and Computational Biology consists of a research and development project worth a minimum of 9 graduate credit hours advised by a faculty member affiliated with the BCB Program. A thesis proposal must be approved by the BCB Program Review Board and the student's advisor before the student can register for more than three thesis credits. The student must satisfactorily complete a written thesis document, and present the results to the BCB faculty in a public presentation.

BCB 699. Ph.D. Dissertation Research

A Ph.D. thesis in Bioinformatics and Computational Biology consists of a research and development project worth a minimum of 30 graduate credit hours advised by a faculty member affiliated with the BCB Program. Students must pass a qualifying exam before the student can register for Ph.D. thesis credits. The student must satisfactorily complete a written dissertation, and defend it in a public presentation and a private defense.

Biology and Biotechnology

www.wpi.edu/+bio

Faculty

J. B. Duffy, Associate Professor and Department Head; Ph.D., University of Texas; defining signaling pathways that program cellular diversity.

D. S. Adams, Professor; Ph.D., University of Texas; neurotrophic factors as potential treatments for stroke and Alzheimer's disease.

T. Dominko, Associate Professor; D.V.M., Ph.D., University of Wisconsin-Madison; investigation of the molecular basis of stem cell gene activation and induced pluripotency.

R. D. Hegedus, Assistant Research Professor; Ph. D., University of Massachusetts at Amherst. purification of biomolecules on the lab scale, process development, scale-up to manufacture, and operational improvement.

A. L. Manning, Assistant Professor; Ph.D., Dartmouth University-Geisel School of Medicine; cancel biology, cell cycle regulation, mitotic progression and chromosome segregation, chromatin regulation, and genome stability.

L. M. Mathews, Associate Professor; Ph.D., University of Louisiana; plant-insect coevolution, agricultural ecology, design and application of molecular genetic tools for ecological research, conservation biology.

K. K. Oates, Professor and Dean of Arts & Sciences; Ph.D., The George Washington University Biochemistry; thymic hormone characterization, monoclonal antibody production, immunology of disease, undergraduate STEM education, STEM Education for Development.

S. M. Politz, Associate Professor; Ph.D., UCLA; genetic control of surface composition in the nematode *C. elegans* as an adaptive mechanism in nematode parasitism.

R. P. Rao, Associate Professor; Ph.D., Penn State University-Medical School; M.S (Dual), Drexel University; emerging Infectious diseases, virulence and host defense mechanisms.

J. Rulfs, Associate Professor; Ph.D., Tufts University; cell culture model systems of signal transduction, metabolic effects of phytoestrogens, cultured cells in tissue engineering.

E. F. Ryder, Associate Professor; Ph.D., Harvard University; M.S., Harvard School of Public Health; bioinformatics and computational approaches to understanding biological systems.

S. S. Shell, Assistant Professor; Ph.D., University of California San Diego; understanding how stress response in pathogenic mycobacterium govern regulation of gene expression and virulence during infection.

J. Srinivasan, Assistant Professor; Ph.D., University of Tuebingen, Germany; defining how neurons interpret social signals both individually and as members of a circuit to produce specific behaviors.

L. Vidali, Associate Professor; Ph.D., University of Massachusetts-Amherst; understanding the molecular and cellular mechanisms underlying the role of the cytoskeleton in plant cell organization and growth.

P. J. Weathers, Professor; Ph.D., Michigan State University; investigation of *Artemisia annua* antimalarial, antimicrobial drug production in *planta*, and bioavailability and therapeutic efficacy *in vitro* and *in vivo*.

Research Interests

Faculty in the Biology and Biotechnology Department has research interests in a range of areas including but not limited to the research foci listed below. Students seeking a graduate degree in biology and biotechnology engage in directed study with one of the department's faculty in his or her research specialty area. The department strongly recommends that, prior to applying, students review the information at the department's Website (www.wpi.edu/+bbt) to help identify potential faculty advisors.

Molecular and Cellular Biology and Biotechnology

Areas of focus: Cytoskeletal dynamics, epigenetics/gene regulation, and signal transduction mechanisms

Biological systems: *C. elegans, Drosophila, M. musculus, Physcomitrella*, and *C. albicans, S. cerevisae,* Cultured cells

Faculty: Dave Adams, Tanja Dominko, Joe Duffy, Amity Manning, Lauren Mathews, Sam Politz, Reeta Rao, Jill Rulfs, Liz Ryder, Scarlet Shell, Jagan Srinivasan and Luis Vidali.

Development, Neurobiology, and Organismal Biology and Biotechnology

Areas of focus: Cancer biology, regenerative medicine, neuronal migration, circuits, and degeneration, pathogenic mechanisms, and plant biology

Model systems: *C. elegans, Drosophila, M. musculus, Physcomitrella, Bombus spp.*, and *C. albicans,* Cultured cells

Faculty: Dave Adams, Tanja Dominko, Joe Duffy, Amity Manning, Sam Politz, Reeta Rao, Liz Ryder, Scarlet Shell, Jagan Srinivasan, and Luis Vidali.

Behavioral and Environmental Biology and Biotechnology

Areas of focus: Animal behavior, biological diversity, brain plasticity, pollinator ecology, and plant biology

Model systems: *Bombus spp., Danaus plexippus, Orconectes spp.*, and *Drosophila*

Faculty: Joe Duffy, Lauren Mathews, Jagan Srinivasan and Pam Weathers.

Programs of Study

With the advent of genomics, the 21st Century has been termed a "revolutionary" era in Biology and Biotechnology. The Department of Biology and Biotechnology (BB) is perfectly situated for this transition with the construction of the Interdisciplinary Life Sciences and Bioengineering Center at Gateway Park. This state-of-the-art building integrates Life Sciences and Bioengineering at WPI in addition to housing a number of technology centers and biotechnology start-ups.

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The Department offers a fulltime research-oriented program for incoming graduate students, leading to either a doctor of philosophy (Ph.D.) in Biology and Biotechnology or Masters (M.S.) degree in Biology and Biotechnology. These programs require students to successfully complete a set of required courses in the field and a thesis project or dissertation that applies the basic principles of biology and biotechnology using hypothesis driven experimental methods to address a specific research problem.

Graduates will have a broad knowledge of the field of biology and biotechnology, a detailed knowledge in their area of specialization, a working knowledge of modern research tools, a strong appreciation for scientific research in theoretical and experimental areas, and a foundation for lifelong learning and experimenting, both individually and as part of a team. Students who complete these programs will be well prepared for careers in the academics and private sectors or further graduate education.

Application and Admission

Applications should be made to either the M.S. or Ph.D. program in biology and biotechnology. The department accepts applications for admission to the Fall semester only.

Admission Requirements

See page 11.

Degree Requirements

Ph.D. in Biology and Biotechnology

In addition to the WPI requirements, a dissertation (minimum of 30 credit hours) and dissertation defense is required of all Ph.D. students. It is the intention of the faculty that doctoral students develop skills not only in their research area, but also receive training in interdisciplinary approaches to research, presentation skills (oral and written), pedagogical approaches, experimental design, and professional ethics within the life sciences. Specific operational details of the program, including the qualifying exam and dissertation defense, can be found in the Biology and Biotechnology graduate handbook.

Publications

All successful Ph.D. students are expected to have at least one author-manuscript published or accepted for publication in a peer-reviewed journal. In addition, the students are required to present their thesis work at a national or international conference.

Qualifying Exam, Reports and Dissertation Defense

A Ph.D. qualifying exam is required and should be taken towards the end of the second year of study. A majority of the Examining Committee must be members of the Biology and Biotechnology department faculty. The committee must also approve the student's dissertation research proposal and review student's progress through committee meetings. Candidates for the Ph.D. degree must give annual presentations of their research work to the department as part of the graduate seminar course. A public defense of the completed dissertation is required of all students and will be followed immediately by a defense before the Examining Committee. All members of the Examining Committee must be present for the defense.

M.S. in Biology and Biotechnology (thesis-based)

Students pursuing the M.S. degree in Biology and Biotechnology must successfully complete a minimum of 30 credit hours of course and thesis work per the distribution requirement below. All courses must be at the 500 or 4000 level and no more than 9 credits may be at the 4000 level. An approved list is provided in the department's graduate handbook.

Credit Requirement:

Course work at the 500 or 4000 level	15 CR
Thesis Research	15 CR (recommended)

Course Requirement:

BB 554 Journal Club	1 CR
BB 551 Research Integrity in the Sciences	1 CR
BB 501 Seminar	1 CR (minimum of 4)
BB course(s)	3 CR
Electives (approved by Advisory Committee)	6 CR
BB 599 Thesis Research	15 CR (recommended)

Students must assemble an Advisory Committee of three or more faculty members of which a majority must be Biology and Biotechnology program faculty members. The Advisory Committee must review and approve each M.S. student's program of study and thesis research. Students must successfully complete a thesis including a written thesis and oral defense.

M.S. in Biotechnology (skills-based):

Students pursuing skills-based M.S. degree in Biotechnology must complete a minimum of 30 credit hours beyond the bachelor's degree. Students enrolled in the M.S. in Biotechnology program must successfully complete 15 credit hours of BB courses, 9 credit hours of skills-based courses, chosen from an approved list provided below and 6 credit hours of elective courses. All courses must be at the 500 or 4000 level and no more than 9 credits may be at the 4000 level. An approved list is provided below. Additional courses will require approval of graduate co-ordinator.

Credit Requirement:

BB courses (at the 500 or 4000 level)	15 CR
Electives (approved by advisory committee)	6 CR
Skills-based courses (**)	9 CR

Approved list of courses for Skills-based M.S. degree in Biotechnology

Courses

- BB 501 Seminar
- BB 570 Special Topics
- BB 551 Research Integrity in the Sciences
- BB 552 Scientific Writing and Proposal Development
- ** BB 553 Experimental Design and Statistics in the Life Sciences
- BB 554 Journal
- BB 556 Mentored Teaching Experience
- BB 515 Environmental Change: Problems and Approaches
- ** BB 505 Fermentation Biology
- ** BB 5xx Animal Cell Culture
- ** BB 509 Scale Up of Bioprocessing
- ** BB 560 Methods of Protein Purification and Downstream Processing
- BB 565 Virology
- BB 561 Model Systems: Experimental Approaches and Applications

BB 562 Cell Cycle Regulation
BB 575 Advanced Genetics and Cellular Biology
** BB 581 Bioinformatics
** BB 598 Directed Research
** BB 4xxx Capstone courses

Related Courses

** BCB 502 Biovisualization
CH 540 Regulation of Gene Expression
CH 555 Advanced Topics
CH 560 Current Topics in Biochemistry
** CH 561 Functional Genomics
CH 4110 Biochemistry I
CH 4120 Biochemistry II
CH 4130 Biochemistry III
** CH 516 Chemical Spectroscopy
** CH 536 NMR Spectroscopy
CH 538 Medicinal Chemistry
CH 541 Membrane Biophysics
** CH 554 Molecular Modeling
CHE 521 Biochemical Engineering
** BME 562 Small animal surgery
** BME 550 Tissue Engineering
MIS 576 Project Management
FIN 500 Financial information in Management

Research Facilities and Centers

Life Sciences and Bioengineering Center (LSBC)

Located in Gateway Park, the world-class, 124,600-square-foot LSBC was built in 2007 and serves as the school's focal point for graduate education and research in the life sciences and related bioengineering fields. It's also home to life sciences companies, state-of-the-art core facilities, and WPI's Corporate and Professional Education division.

The Core facilities include an Imaging core providing a wide range of imaging capabilities for live and fixed samples including Confocal microscopy with FRET and FRAP, Atomic Force Microscopy, and microinjection/manipulation and histology capabilities; an Analytical core, with NMR, Atomic-absorption (AA) spectroscopy, LC-MS and GC-MS capabilities; and Molecular Cores for DNA/RNA/tissue work. Additional shared common spaces include centralized facilities for waste disposal, media preparation as well as dishwashing. The facility is part of the WPI-University of Massachusetts Consortium which allows researchers at both institutions to access facilities and services at the other institution at "in-house" rates.

Bioprocess Center (BPC)

Researchers at the BPC design and develop scalable processes for drug manufacturing. The BPC contracts with biotechnology companies, to supply drug targets in research quantities and conduct lab- and pilot-scale process development.

Biomanufacturing Education and Training Center (BETC)

WPI's Biomanufacturing Education and Training Center, the first of its kind in the Northeast, provides innovative workforce development solutions customized to the specific needs of an industry. Serving life sciences companies from across the region and the globe, the center represents an innovative partnership of academia and industry by offering hands-on and classroom training by experts in a wide-range of roles and disciplines.

Course Descriptions

BB 501. Seminar
(1 credit)

BB 505. Fermentation Biology
(3 credits)
Material in this course focuses on biological (especially microbiological) systems by which materials and energy can be interconverted (e.g., waste products into useful chemicals or fuels). The processes are dealt with at the physiological and the system level, with emphasis on the means by which useful conversions can be harnessed in a biologically intelligent way. The laboratory focuses on measurements of microbial physiology and on bench-scale process design.

BB 509. Scale Up of Bioprocessing
(3 credits)
Strategies for optimization of bioprocesses for scale-up applications will be explored. In addition to the theory of scaling up unit operations in bioprocessing, students will scale up a bench-scale bioprocess (5 liters), including fermenta- tion and downstream processing to 55 liters. Specific topics include the effects of scaling up on: mass transfer and bioreactor design, harvesting techniques including tangential flow filtration and centrifugation, and chromatography (open column and HPLC). (Prerequisites: BB 4050/505 and BB 4060/560 as a working knowledge of the bench-scale processes will be assumed. Otherwise, instructor permission is required.)

BB 515. Environmental Change: Problems and Approaches
(3 credits)
This seminar course will examine what is known about ecological responses to both natural and human-mediated environmental changes, and explore approaches for solving ecological problems and increasing environmental sustainability. Areas of focus may include, and are not limited to, conservation genetics, ecological responses to global climate change, sustainable use of living natural resources, and the environmental impacts of agricultural biotechnology.

BB 551. Research Integrity in the Sciences
(1 credit)
Students are exposed to various issues related to integrity in doing research to enable development of an appropriately reasonable course of action in order to maintain integrity on a variety of research-related performance and reporting activities. These activities include, but are not limited to data fabrication, authorship, copyright, plagiarism, unintended dual use of technology, and responsibilities towards peers who may request your confidential review or feedback. The course will use class discussion, case studies, and exercises to facilitate an understanding of the responsibilities of scientists to their profession. Students may receive credit for either BB551 or a BB570 course entitled Research Integrity in the Sciences but not both.

BB 552. Scientific Writing and Proposal Development
(3 credits)
This course will cover key elements to writing successful grant proposals and manuscripts. This includes project development, identification of funding agencies or journals, proposal and manuscript writing and editing, as well as aspects of the submission and review process. Students will be expected to develop a NIH/NSF style postdoctoral proposal outside their dissertation field and participate in a mock proposal review panel. Students are expected to complete this course prior to their Qualifying Exam. Students may receive credit for either BB552 or a BB570 course entitled Scientific Writing and Proposal Development but not both.

BB 553. Experimental Design and Statistics in the Life Sciences
(3 credits)
This applied course introduces students to the basics of experimental design and data analysis. Emphasis will be placed on designing biological experiments that are suitable for statistical analysis, choosing appropriate statistical tests to perform, and interpreting the results of statistical tests. We will cover statistical methods commonly used by biologists to analyze experimental data, including testing the fit of data to theoretical distributions, comparisons of groups, and regression analysis. Both parametric and non-parametric tests will be discussed. Students will use computer packages to analyze their own experimental data. Students may receive credit for either BB553 or a BB570 course entitled Experimental Design and Statistics in the Life Sciences but not both.

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BB 554. Journal Club
(1 credit)
This course is offered every semester covering different topics, both basic and applied, in Biology and Biotechnology and rotates among the faculty. Students read and discuss the literature in relevant topics.

BB 556. Mentored Teaching Experience
(1 credit)
This course is arranged with an individual faculty member within the student's discipline. The graduate student is involved in the development of course materials, such as a syllabus, projects, or quizzes, and course delivery, such as lecturing or facilitating a conference session (20% delivery limit). In addition to covering course pedagogy, the faculty member arranges for the student teacher to be evaluated by students enrolled in the course and reviews the student reports with the student teacher.

BB 560. Methods of Protein Purification and Downstream Processing
(3 credits)
This course provides a detailed hands-on survey of state-of-the-art methods employed by the biotechnology industry for the purification of products, proteins in particular, from fermentation processes. Focus is on methods that offer the best potential for scale-up. Included is the theory of the design, as well as the operation of these methods both at the laboratory scale and scaled up. It is intended for biology, biotechnology, chemical engineering and biochemistry students. (Prerequisite: knowledge of basic biochemistry is assumed.)

BB 561. Model Systems: Experimental Approaches and Applications
(2 credit)
The course is intended to introduce students to the use of model experimental systems in modern biological research. The course covers prokaryotic and eukaryotic systems including microbial (*Escherichia coli*) and single cells eukaryotes (fungi); invertebrate (*Caenorhabditis elegans, Drosophila melanogaster*) and vertebrate (mice, zebra fish) systems and plants (moss, algae and *Arabidopsis thaliana*). Use of these systems in basic and applied research will be examined. Students may receive credit for either BB561 or a BB570 course entitled Model Systems: Experimental Approaches and Applications but not both.

BB 562. Cell Cycle Regulation
(3 credits)
This course focuses on molecular events that regulate cell cycle transitions and their relevance to mammalian differentiated and undifferentiated cells. Topics include control of the G1/S and G2/M transitions, relationships between tumor suppressor genes such as p16, Rb, p53 or oncogenes such as cyclin D, cdc25A, MDM2 or c-myc and cell cycle control. Where appropriate, the focus is on understanding regulation of cell cycle control through transcriptional induction of gene expression, protein associations, posttranslational modifications like phosphorylation or regulation of protein stability like ubiquitin degradation. Students may receive credit for either BB562 or a BB570 course entitled Cell Cycle Regulation but not both.

BB 565. Virology
(3 credits)
This advanced level course uses a seminar format based on research articles to discuss current topics related to the molecular/cell biology of viral structure, function, and evolution. Particular emphasis is placed on pathological mechanisms of various human disorders, especially emerging disease, and the use of viruses in research.

BB 570. Special Topics
(variable credit)
Specialty subject courses are offered based on the expertise of the department faculty such as Stem Cell Biology.

BB 575. Advanced Genetics and Cellular Biology
(3 credits)
Topics in this course focus on the basic building blocks of life: molecules, genes and cells. The course will address areas of the organization, structure, function and analysis of the genome and of cells. (Prerequisite: A familiarity with fundamentals of recombinant DNA and molecular biological techniques as well as cell biology.)

BB 581/BCB 501. Bioinformatics
(3 credits)
This course will provide an overview of bioinformatics, covering a broad selection of the most important techniques used to analyze biological sequence and expression data. Students will acquire a working knowledge of bioinformatics applications through hands-on use of software to ask and answer biological questions. In addition, the course will provide students with an introduction to the theory behind some of the most important algorithms used to analyze sequence data (for example, alignment algorithms and the use of hidden Markov models). Topics covered will include protein and DNA sequence alignments, evolutionary analysis and phylogenetic trees, obtaining protein secondary structure from sequence, and analysis of gene expression including clustering methods. (Prerequisite: knowledge of genetics, molecular biology, and statistics at the undergraduate level.) Students may not receive credit for both BB 581 and BB 4801.

BB 598. Directed Research
Directed research conducted under the guidance of a faculty member in the BB Program.

BB 599. Master's Thesis
A Master's thesis in Biology and Biotechnology consists of a research and development project worth a minimum of 9 graduate credit hours advised by a faculty member in the BB Program. The student must satisfactorily complete a written dissertation, public presentation, and private defense with thesis committee.

BB 699. Ph.D. Dissertation
A Ph.D. thesis in Biology and Biotechnology consists of a research and development project worth a minimum of 30 graduate credit hours advised by a faculty member affiliated with the BB Program. Students must pass a qualifying exam before the student can register for Ph.D. thesis credits. The student must satisfactorily complete a written dissertation, defend in a public presentation and private defense with thesis committee.

Biomedical Engineering

www.wpi.edu/+bme

Faculty

K. L. Billiar, Professor and Department Head; Ph.D., University of Pennsylvania; Biomechanics of soft tissues and biomaterials, mechanobiology, wound healing, tissue growth and development; functional tissue engineering, regenerative medicine.

D. R. Albrecht, Assistant Professor; Ph.D., University of California, San Diego; bioMEMS, microfluidics, quantitative systems analysis and modeling, biodynamics, neural circuits and behavior, optogenetics, high-throughput chemical/genetic screens, tissue engineering, 3-D cell micropatterning, dielectrophoresis.

J. Coburn, Assistant Professor; Ph.D., Johns Hopkins University; biomaterials, scaffolds, tissue engineering, 3-D tissue models, stem cells, cell-matrix/material interactions, drug delivery, oncology therapeutics.

G. R. Gaudette, Professor; Ph.D., SUNY Stony Brook; Cardiac biomechanics, myocardial regeneration, biomaterial scaffolds, tissue engineering, stem cell applications, optical imaging techniques.

S. Ji, Associate Professor; D.Sc., Washington University in St. Louis; Biomechanics, brain injury, finite element analysis, multi-scale modeling, neuroimaging, medical image analysis, sports medicine.

K. Lee, Assistant Professor; Ph.D., Massachusetts Institute of Technology; mechanobiology, cell mechanics, cell morphodynamics, cancer cell migration, quantitative live cell imaging, quantitative cell biology, computational image analysis, data mining, genome engineering, optogenetics.

Y. Mendelson, Professor; Ph.D., Case Western Reserve University; Biomedical sensors for invasive and noninvasive physiological monitoring, pulse oximeters, microcomputer-based medical instrumentation, signal processing, wearable wireless biomedical sensors, application of optics to biomedicine, telemedicine.

G. D. Pins, Associate Professor; Ph.D., Rutgers University; Cell and tissue engineering, biomaterials, bioMEMS, scaffolds for soft tissue repair, cell-material interactions, wound healing, cell culture technologies.

M. W. Rolle, Associate Professor, Ph.D., University of Washington, Seattle; Cardio-vascular tissue engineering, bioreactor design, cell-based tissue repair, cell and molecular engineering, cell-derived extracellular matrix scaffolds, delivery and control of extracellular matrix genes.

K. L. Troy, Associate Professor; Ph.D., University of Iowa; orthopedic biomechanics, multi-scale modeling, finite element analysis, medical image analysis, bone and joint structure.

C. F. Whittington, Assistant Professor; Ph.D., Purdue University; Cell-extracellular matrix interactions, biomaterials, 3D culture, tissue engineering, mechanobiology, disease models, tumor microenvironment, tumor metastasis, phenotypic assay development, high-throughput and high-content screening.

Research Interests

Biological Microtechnology and Neuroengineering

Prof. Albrecht

Research is focused on development of high-content, high-throughput microtechnologies to investigate the function, development, degeneration, and remodeling of neural circuits and biochemical networks. Projects aim to: (1) understand the molecular and genetic basis of neural circuit function and dynamics, (2) develop rapid cellular and whole-organism screens for therapeutic drugs and genetic modulators of neural disease, (3) develop computational models and bioinformatic tools to analyze phenotypic and neural data, (4) map neuropeptide signaling pathways.

Biomaterials/Tissue Engineering

Prof. Pins

Research focuses on understanding the interactions between cells and precisely bioengineered scaffolds that modulate cellular functions such as adhesion, migration, proliferation, differentiation and extracellular matrix remodeling. Understanding cell-matrix interactions that regulate wound healing and tissue remodeling will be used to improve the design of tissue-engineered analogs for the repair of soft and hard tissue injuries. Research areas include: (1) development of biopolymer microthreads with tunable mechanical and biochemical properties to direct tissue regeneration, (2) development of tissue scaffolds that mimic the microstructural organization and mechanical responsiveness of native tissues, and (3) development of microfabricated scaffold and model systems to understand how extracellular matrix molecules regulate cell and tissue growth and differentiation.

Biomedical Sensors and Bioinstrumentation

Prof. Mendelson

The development of integrated biomedical sensors and electronic instrumentation for invasive and noninvasive blood monitoring. Research areas include:

- Design and in vivo evaluation of reflective pulse oximeter sensors.
- Microcomputer-based medical instrumentation
- Fiberoptic sensors for medical instrumentation
- Application of optics to biomedicine
- Signal processing
- Telesensing
- Wearable physiological monitoring

Brain Injury Biomechanics

Prof. Ji

Research focuses on developing sophisticated, yet efficient computational techniques to better understand the mechanisms of brain injury, and to aid in more effective injury diagnosis especially in sports-related concussion. Research areas include: 1) developing multi-scale modeling techniques to study brain injury biomechanics; 2) integrating neuroimaging into biomechanical models of the brain for injury analysis; 3) substantially improving the efficiency in computational modeling; and 4) integrating with head impact sensors to facilitate brain injury diagnosis on the sports field.

Cardiac Tissue Engineering & Regeneration

Prof. Gaudette

Research is focused on revascularizing and regenerating functional myocardial tissue to replace dysfunctional heart tissue. Projects focus on understanding the interaction of the local mechanical and electrical environment with the mechanisms of cardiac regeneration include myocyte proliferation and adult stem cell differentiation. Research areas include (1) development of scaffolds to induce myocardial regeneration, (2) differentiation of progenitor cells into cardiac cells, (3) determination of cues in the microenvironment that affect myocardial regeneration.

Engineered Tissue Models for High Throughput Screening

Prof. Whittington

Research focuses on combining bio-instructive biomaterials with cells to design 3D tissue-engineered platforms for regenerative medicine, disease modeling, improved predictability of therapeutic outcomes, and as translatable technologies for clinic and industry. Projects aim to: 1) design physiologically relevant microenvironments for single and multi-tissue restoration and reintegration, 2) recreate biophysical and biochemical regulation of signaling pathways for mechanistic study of diseased tissue development, progression, interactions, and therapeutic response, and 3) adapt and/or create platforms for use in high-throughput and high-content screening of functional outcomes for improved validation and efficacy studies.

Functional Biomaterials

Prof. Coburn

Research focuses on developing biomaterials-based approaches for tissue engineering and regenerative medicine as well as drug delivery therapeutics. Research interests include (1) 3-D biomaterial scaffolds for functional hepatic tissue engineering, (2) 3-D biomaterials scaffolds for biomimetic, in vitro oncology models, (3) understanding the role of multiple cell types in tissue/disease maturation, (4) engineered drug delivery systems for cancer treatment, and (5) investigating the mechanisms of drug-material interactions via structure-function relationships.

Musculoskeletal Biomechanics

Prof. Troy

Dr. Troy's research takes a biomechanics approach to understanding how physical forces applied to the musculoskeletal system (generated through exercise or other physical activity) influence bone and joint structure, health, and disease. Her experimental approach utilizes cadaveric experimentation, medical image analysis, patient-specific computational models, and living human subjects. The laboratory currently focuses on three projects: (1) Development, validation, and application of noninvasive and sensitive methods to measure bone strength in living human subjects. (2) Quantifying the mechanical signals that are applied to the skeleton through physical activity and understanding their influence on bone structure. (3) Quantifying the effect of disease-related changes to bone structure and joint kinetics on tissue mechanical loading environment. Other collaborative projects relate to using biomechanics-based outcome measures to assess the effect of interventions affecting the musculoskeletal system in humans and other organisms.

Quantitative Mechanobiology of Cell Morphodynamics

Prof. Lee

Research is focused on developing novel methodologies for quantitative measurement and manipulation of cellular activities to investigate mechanobiology of cell morphodynamics. Research areas include (1) high throughput quantitative imaging to characterize dynamics and coordination of molecular/mechanical events in living cells, (2) quantitative control of protein expression using optogenetics, genome engineering, and imaging, (3) data mining of large-scale time series of molecular/mechanical events, and (4) mechanobiology of cancer cell migration.

Soft Tissue Biomechanics/ Tissue Engineering

Prof. Billiar

Research focused on understanding the growth and development of connective tissues and on the influence of mechanical stimulation on cells in native and engineered three-dimensional constructs. Research areas include: (1) micromechanical characterization of tissues, (2) constitu tive modeling, (3) creation of bioartificial tissues *in vitro,* and (4) the effects of mechanical stimulation on the functional properties of cells and tissues.

Tissue Engineering & Matrix Scaffolds

Prof. Rolle

Research focuses on the role of extracellular matrix proteins on tissue mechanical and functional properties in the context of tissue engineering and regenerative medicine. Research interests include (1) genetic engineering strategies to control cell-mediated matrix synthesis and assembly, (2) cell-based approaches to generating tissue engineered blood vessels, (3) evaluating the contribution of matrix molecules to the mechanical and functional properties of scaffolds, and tissues, (4) developing matrix gene delivery systems to promote tissue regeneration.

Programs of Study

The goal of the biomedical engineering (BME) graduate programs is to apply engineering principles and technology as solutions to significant biomedical problems. Students trained in these programs have found rewarding careers in major medical and biomedical research centers, academia, the medical care industry and entrepreneurial enterprises.

Master's Degree Programs

There are two master's degree options in biomedical engineering: the Master of Science (M.S.) in Biomedical Engineering, and the Master of Engineering (M.E.) in Biomedical Engineering. While the expected levels of student academic performance are the same for both options, they are oriented toward different career goals. The master of science option in biomedical engineering is oriented toward the student who wants to focus on a particular facet of biomedical engineering practice or research. The master of science can serve as a terminal degree for students interested in an indepth specialization.

Doctoral Programs

The degree of doctor of philosophy in Biomedical Engineering is conferred on candidates in recognition of high attainments and the ability to carry on original independent research. Graduates of the program will be prepared to affiliate with academic institutions and with the growing medical device and biotechnology industries which have become major economic clusters in the Commonwealth of Massachusetts.

Combined B.S./Master's Degree Program

This program affords an opportunity for outstanding WPI undergraduate students to earn both a B.S. degree and a master's degree in biomedical engineering concurrently, and in less time than would typically be required to earn each degree separately. The principal advantage of this program is that it allows for certain credits to be counted towards both degree requirements, thereby reducing total class time. With careful planning and motivation, the Combined Program typically allows a student to complete requirements for both degrees with only one additional year of full-time study (five years total). However, because a student must still satisfy all graduate degree requirements, the actual time spent in the program may be longer than five years. There are two degree options for students in the Combined Program: a thesis- based master of science (B.S./M.S.) option and a non-thesis master of engineering (B.S./M.E.) option. The Combined B.S./Master's Degree Program in BME adheres to WPI's general requirements for the Master of Science and Master of Engineeering.

Admission Requirements

Biomedical engineering embraces the application of engineering to the study of medicine and biology. While the scope of biomedical engineering is broad, applicants are expected to have an undergraduate degree or a strong background in engineering and to achieve basic and advanced knowledge in engineering, life sciences, and biomedical engineering. Special programs are available for outstanding graduates lacking the necessary prerequisites or with a background in the physical or life sciences. These special programs typically involve an individualized plan of coursework at the advanced undergraduate level, with formal admittance to the program following the successful completion (with grades of B or higher) of this coursework.

Degree Requirements

For the M.S.

A minimum of 30 credit hours is required for the Master of Science degree, of which at least 6 credit hours must be a thesis. Course requirements include 9 credits of biomedical engineering, 3 credits of life science, 3 credits of advanced mathematics, 3 credits of life science or advanced mathematics, and 6 credits of electives (any WPI graduate-level engineering, physics, math, biomedical engineering, or equivalent course, subject to approval of the department Graduate Studies Committee). Students are required to pass BME 591: Graduate Seminar twice.

For the M.E.

A minimum of 33 credit hours is required for the Master of Engineering degree. Course requirements include 12 credits of biomedical engineering, 3 credits of life science, 3 credits of advanced mathematics, 3 credits of life science or advanced mathematics, and 12 credits of electives (any WPI graduate-level engineering, physics, math, biomedical engineering, or equivalent course, subject to approval of the department Graduate Studies Committee). Students may substitute 3 to 6 credits of directed research for 3 credits of biomedical engineering and/or 3 credits of electives. Students are required to pass BME 591: Graduate Seminar twice.

For the Ph.D.

The Ph.D. program has no formal course requirements. However, because research in the field of biomedical engineering requires a solid working knowledge of a broad range of subjects in the life sciences, engineering and mathematics, course credits must be distributed across the following categories with the noted minimums: 12 credits of biomedical engineering, 3 credits of life science, 3 credits of advanced mathematics, 3 credits of life science or advanced mathematics, and 12 credits of electives (any WPI graduate-level engineering, physics, math, biomedical engineering, or equivalent course, subject to approval of the department Graduate Studies Committee). Ph.D. program students must also complete 6 credits of laboratory rotations, 1 credit of responsible conduct of research, and 30 credits of dissertation research.

The student's Academic Advisory Committee may require additional coursework to address specific deficiencies in the student's background. Students are required to pass BME 591: Graduate Seminar four times.

No later than the start of the third year after formal admittance to the Ph.D. program, students are required to pass a Ph.D. qualifying examination. This examination is a defense of an original research proposal, made before a committee representative of the area of specialization. The examination is used to evaluate the ability of the student to pose meaningful engineering and scientific questions, to propose experimental methods for answering those questions, and to interpret the validity and significance of probable outcomes of these experiments. It is also used to test a student's comprehension and understanding of their formal coursework in life sciences, biomedical engineering and mathematics. Admission to candidacy is officially conferred upon students who have completed their course credit requirements, exclusive of dissertation research credit, and passed the Ph.D. qualifying examination.

Students in the Ph.D. program are required to participate in at least two different laboratory rotations during their first two years in the program. Laboratory rotations—short periods of research experience under the direction of program faculty members—are intended to familiarize students with concepts and techniques in several different engineering and scientific fields. They allow faculty members to observe and evaluate the research aptitudes of students and permit students to evaluate the types of projects that might be developed into dissertation projects. Upon completion of each rotation, the student presents a seminar and written report on the research accomplished. Each rotation is a 3- or 4-credit course and lasts a minimum of eight weeks if the student participates full time in the laboratory, or up to a full semester if the student takes courses at the same time.

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All candidates for the Ph.D. degree must demonstrate teaching skills by preparing, presenting and evaluating a teaching exercise. This experience may involve a research seminar, lecture, demonstration or conference in the context of a medical school basic science course. Formal parts of the presentation may be videotaped as appropriate. The presentation and associated materials are critiqued and evaluated by program faculty members. The department Graduate Studies Committee is responsible for evaluating the teaching exercise based on criteria previously defined. The teaching requirement can be fulfilled at any time, and there is no limit to the number of attempts a student may make to fulfill this requirement. It must, however, be completed successfully before the dissertation defense can be held.

The Ph.D. program requires a full-time effort for a minimum of three years and does not require a foreign language examination.

Research Laboratories and Facilities

Research is primarily conducted in a new four-story, 124,600-square-foot Life Sciences and Bioengineering Center (LSBC) located at Gateway Park. This space is largely dedicated to research laboratories that focus on non-invasive biomedical instrumentation design, signal processing, tissue biomechanics, biomaterials synthesis and characterization, myocardial regeneration, cell and molecular engineering, regenerative biosciences and tissue engineering. The LSBC research facility also maintains a modern core equipment facility that includes cell culture, histology, imaging and mechanical testing suites to support cellular, molecular, and tissue engineering research activities.

A brief description of BME research laboratories is given below.

Biological Microtechnology and Neuroengineering

The laboratory develops microtechnologies to understand complex biological networks towards improving the treatment of human disease. A particular focus is uncovering the molecular and genetic basis of neural dynamics in normal, injured, and diseased nervous systems. Projects involve quantitative, high-content analysis of animal behavior and neural activity, noninvasive and genetic neuromodulation, and integrated microfluidics for precise stimulus delivery. Research equipment includes fast ultrasensitive fluorescence microscopes for optogenetic recordings, molecular biology and microinjection systems for generating transgenic animals, microfabrication systems for microfluidic arenas, and robotic fluid handling for chemical screening.

Biomedical Sensors and Bioinstrumentation

The development of integrated biomedical sensors for invasive and noninvasive physiological monitoring. Design and in-vivo evaluation of reflective pulse oximeter sensors, microcomputer-based biomedical instrumentation, digital signal processing, wearable wireless biomedical sensors, application of optics to biomedicine, telemedicine.

Biomaterials/Tissue Engineering

Research focuses on understanding the interactions between cells and precisely bioengineered scaffolds that modulate cellular functions such as adhesion, migration, proliferation, differentiation and extracellular matrix remodeling. Understanding cell-matrix interactions that regulate wound healing and tissue remodeling will be used to improve the design of tissue-engineered analogs for the repair of soft and hard tissue injuries. Research areas include: (1) studies investigating the roles of microfabricated scaffolds on keratinocyte function for tissue engineering of skin; (2) development of tissue scaffolds that mimic the microstructural organization and mechanical responsiveness of native tissues; and (3) development of microfabricated cell culture systems to understand how extracellular matrix molecules regulate epithelial cell growth and differentiation.

Cardiovascular Regeneration

Research projects focus on regenerating functional cardiac muscle tissue. Research areas include: (1) stimulating adult cardiac myocytes, a cell previously considered to be post-mitotic, to enter the cell cycle; (2) differentiating adult stem cells into cardiac myocytes; and (3) scaffold based cardiac regeneration. The efficacy of these technologies are tested with *in vitro* and *in vivo* models using molecular and cellular tools and the functionality is assessed using high spatial resolution mechanical and electrical method.

Cardiovascular Tissue Engineering and Extracellular Matrix Biology

The extracellular matrix (ECM) produced by cells dictates tissue architecture and presents biochemical signals that direct cell proliferation, differentiation and migration. Generating an appropriate ECM is critical for proper physiological and mechanical performance of engineered tissues. Research projects include: (1) design and testing of genetic and biochemical engineering strategies to stimulate cellular ECM synthesis and organization, (2) cell-based approaches to generate tissue engineered blood vessels (TEBV), (3) evaluation of ECM production and its effect on TEBV mechanical properties, and (4) ECM gene delivery approaches for in situ tissue regeneration.

Cellular Mechanobiology and Quantitative Imaging

The laboratory is focusing on quantitative understanding of cellular mechanobiology to come up with new therapeutics for cancer metastasis. Our method is integrating quantitative imaging, genome engineering, and optogenetics for precision measurement and manipulation of cell states. The research equipment includes spinning disk confocal microscope for live cell imaging, optogenetic gene expression systems, multiplex genome engineering tools, magnetic tweezers, high performance workstations, and advanced image analysis platform for cell morphodynamics, fluorescent speckle imaging, single particle tracking, and traction force reconstruction.

Musculoskeletal Biomechanics Laboratory

The laboratory develops and validates image analysis and computational modeling techniques to noninvasively estimate stresses and strains occurring within the skeleton of living humans. Quantitative computed tomography (QCT) analysis is a primary tool for measuring the amount and distribution of hydroxyapatite mineral present within bone. These images can be used as a basis for generating subject or specimen-specific finite element models to predict mechanical behavior. Simulation experiments are used to determine the consequences of clinical conditions or interventions that affect bone and

joint structure and boundary conditions. Specialized research equipment includes high resolution peripheral quantitative CT instrumentation, which can acquire near micro-resolution CT data within the extremities of living human subjects. A materials testing machine and strain gages are used for cadaveric experimentation.

Soft Tissue Biomechanics/ Tissue Engineering

Research focused on understanding the growth and development of connective tissues and on the influence of mechanical stimulation on cells in native and engineered three-dimensional constructs. Research areas include: (1) micromechanical characterization of tissues, (2) constitutive modeling, (3) creation of bioartificial tissues in vitro, and (4) the effects of mechanical stimulation on the functional properties of cells and tissues.

Course Descriptions

All courses are 3 credits unless otherwise noted.

BME 523. Biomedical Instrumentation

Origins and characteristics of bioelectric signals, recording electrodes, biopotential amplifiers, basic sensors, chemical, pressure, sound, and flow transducers, noninvasive monitoring techniques and electrical safety. (Prerequisites: Circuits and electronics, control engineering or equivalent.)

BME 531. Biomaterials in the Design of Medical Devices

Biomaterials are an integral part of medical devices, implants, controlled drug delivery systems, and tissue engineered constructs. Extensive research efforts have been expended on understanding how biologic systems interact with biomaterials. Meanwhile, controversy has revolved around biomaterials and their availability as a result of the backlash to the huge liability resulting from controversies related to material and processing shortcomings of medical devices. This course specifically addresses the unique role of biomaterials in medical device design and the use of emerging biomaterials technology in medical devices. The need to understand design requirements of medical devices based on safety and efficacy will be addressed. Unexpected device failure can occur if testing fails to account for synergistic interactions from chronic loading, aqueous environments, and biologic interactions. Testing methodologies are readily available to assess accelerated effects of loading in physiologic-like environments. This combined with subchronic effects of animal implants is a potential tool in assessing durability. It is difficult to predict the chronic effects of the total biologic environment. The ultimate determination of safety comes not only from following the details of regulations, but with an understanding of potential failure modes and designs that lowers the risk of these failures. This course will evaluate biomaterials and their properties as related to the design and reliability of medical devices.

BME 532. Medical Device Regulation

This course provides an overview of regulations that guide the medical devices industry. Primary focus is on the Food, Drug and Cosmetic Act (FD&C Act) and its associated regulations. The course covers the FD&C Act, including definitions, prohibited acts, penalties and general authority. The course also covers regulations, including establishment registration, premarket approval (PMA) and current good manufacturing practices. Requirements of other federal agencies (NRC, FCC, EPA) will also be discussed.

BME/ME 550. Tissue Engineering

This biomaterials course focuses on the selection, processing, testing and performance of materials used in biomedical applications with special emphasis upon tissue engineering. Topics include material selection and processing, mechanisms and kinetics of material degradation, cell-material interactions and interfaces; effect of construct architecture on tissue growth; and transport through engineered tissues. Examples of engineering tissues for replacing cartilage, bone, tendons, ligaments, skin and liver will be presented. (Prerequisites: A first course in biomaterials equivalent to BME/ME 4814 and a basic understanding of cell biology and physiology. Admission of undergraduate students requires the permission of the instructor.)

BME/ME 552. Tissue Mechanics

This biomechanics course focuses on advanced techniques for the characterization of the structure and function of hard and soft tissues and their relationship to physiological processes. Applications include tissue injury, wound healing, the effect of pathological conditions upon tissue properties, and design of medical devices and prostheses. (Prerequisite: An understanding of basic continuum mechanics.)

BME 555. BioMEMS and Tissue Microengineering

This course covers microscale biological and physical phenomena and state-of-the-art techniques to measure and manipulate these processes. Topics include scaling laws, microfabrication, machining three-dimensional microstructures, patterning biomolecules, and designing and building microfluidic devices. We will cover various biomedical problems that can be addressed with microfabrication technology and their associated engineering challenges, with special emphasis on applications related to quantitative biology, tissue microengineering, controlling the cellular microenvironment, and clinical/diagnostic lab-on-a-chip devices.

BME 560. Physiology for Engineers

An introduction to fundamental principles in cell biology and physiology designed to provide the necessary background for advanced work in biomedical engineering. Quantitative methods of engineering and the physical sciences are stressed. Topics include cell biology, DNA technology and the physiology of major organ systems.

NOTE: This course can be used to satisfy a life science requirement in the biomedical engineering program. It cannot be used to satisfy a biomedical engineering course requirement.

BME 562. Laboratory Animal Surgery

A study of anesthesia, surgical techniques and postoperative care in small laboratory animals. Anatomy and physiology of species used included as needed. Class limited to 15 students. Approximately 15 surgical exercises are performed by each student. (Prerequisite: Graduate standing. Admission of undergraduate students requires the permission of the department head and the instructor.)

NOTE: This course can be used to satisfy a life science requirement in the biomedical engineering program. It cannot be used to satisfy a biomedical engineering course requirement.

BME 564. Cell and Molecular Biology for Engineers

An advanced course in cell and molecular biology for engineering graduate students, with an emphasis on molecular approaches to measuring and manipulating cell responses for biomedical engineering applications. Course topics will include in depth exploration of the molecular basis of cellular function, including protein biochemistry, signal transduction, cell-extracellular matrix interactions and regulation of gene expression. Tools and techniques used in modern cell and molecular biology will be discussed in the context of current research literature.

NOTE: This course can be used to satisfy a life science requirement in the graduate biomedical engineering program. It cannot be used to satisfy a biomedical engineering course requirement (undergraduate or graduate).

BME 581. Medical Imaging Systems

Overview of the physics of medical image analysis. Topics covered include X-Ray tubes, fluoroscopic screens, image intensifiers; nuclear medicine; ultrasound; computer tomography; nuclear magnetic resonance imaging. Image quality of each modality is described mathematically, using linear systems theory (Fourier transforms, convolutions). (Prerequisite: Signal analysis course BME/ECE 4011 or equivalent.)

BME 583. Biomedical Microscopy and Quantitative Imaging

This course introduces fundamental principles of biomedical imaging focused on quantitative microscopy. Topics include physical basis of light microscopy, fluorescence microscopy, live cell imaging and computer vision algorithms. Advanced topics include 3D imaging (confocal, light sheet, 2-photon), super-resolution, sample preparation, and equipment considerations. Selected topics in medical imaging (CT, MRI, ultrasound) may be included, with hands-on instruction on commercial and student-built systems.

NOTE: Students who received credit for BME 581 in Spring 2016 may not also receive credit for BME 583.

BME 591. Graduate Seminar

(0 credits)

Topics in biomedical engineering are presented both by authorities in the field and graduate students in the program. Provides a forum for the communication of current research and an opportunity for graduate students to prepare and deliver oral presentations. Students may meet the attendance requirement for this course in several ways, including attendance at weekly biomedical engineering seminars on the WPI campus, attendance at similar seminar courses at other universities or biotech firms, attendance at appropriate conferences, meetings or symposia, or in any other way deemed appropriate by the course instructor.

BME 594. Biomedical Engineering Journal Club

(1 credit)

This course will cover different topics in biomedical engineering research, both basic and translational. Enrolled students read and discuss the literature in relevant topics, which may include biomaterials, drug delivery, tissue engineering, cardiovascular engineering, mechanobiology, quantitative imaging, instrumentation, computational biomechanics, injury and rehabilitative biomechanics, or any focused topic related to biomedical engineering. The objectives of the course are for students to learn about current topics within a focused area of biomedical engineering, to improve their ability to critically review literature, and develop their technical presentation skills. Multiple sections of biomedical engineering journal club focused on different research topics may be offered each semester. (Pre-requisite: Master's or Ph.D. student in biomedical engineering or a related discipline).

Biomedical engineering graduate students may take up to 3 credits of BME 594 to satisfy Biomedical Engineering or Elective course credit to meet graduate program distribution requirements.

NOTE: This course cannot be used to satisfy Biomedical Engineering or Engineering elective credit to meet undergraduate program distribution requirements.

BME 595. Special Topics in Biomedical Engineering

(1-3 credits)

Topics in biomedical engineering. Presentations and discussions of the current literature in an area of biomedical engineering.

BME 596. Research Seminar

Presentations on current biomedical engineering research.

BBME 598. Directed Research

Students may register for Directed Research to fulfill graduate research rotation (e.g. Master's students seeking a thesis lab) or independent, mentored graduate research and projects. BME graduate students may apply up to 3 credits of BME 598 as BME course credit and an additional 3 credits of BME 598 credit to fulfill elective, laboratory rotation, or independent project credit. BME 598 credit used for laboratory rotations may be converted to BME 599 or BME 699 credit for qualified graduate students who remain in the rotation laboratory for their thesis or dissertation research. (Pre-requisite: Master's or Ph.D. student in biomedical engineering).

BME 599. Master's Thesis

Graduate students enrolled in the thesis-based (Master of Science, M.S.) program must complete 6 credits total and successfully defend and submit a Master's thesis by the posted deadlines. (Pre-requisite: Master's thesis student in biomedical engineering).

BME 698. Laboratory Rotation in Biomedical Engineering

Offered fall, spring and summer for students doing laboratory rotations on the WPI campus. Available for 3 or 4 credits. (Prerequisite: Ph.D. student in biomedical engineering.)

BME 699. Ph.D. Dissertation

All Ph.D. students must complete 30 credits of dissertation research to fulfill Ph.D. degree requirements. (Pre-requisite: Student has passed the Biomedical Engineering Ph.D. Qualifying Examination).

Robert A. Foisie School of Business

business.wpi.edu

Faculty

M. Ginzberg, Dean and Professor; Ph.D., Massachusetts Institute of Technology; management of technology and technical professionals, creating business value through investments in technology, management of risk, corporate governance.

J. Sarkis, Professor and Department Head; Ph.D., State University of New York at Buffalo; operations management, green supply chain management, sustainability.

S. Djamasbi, Associate Professor; Ph.D., University of Hawaii at Manoa; decision making, decision support systems, information overload, decision making under crisis, affect and decision making.

M. B. Elmes, Professor; Ph.D., Syracuse University; workplace resistance and ideological control, critical perspectives on spirituality-in-the-workplace, implementation of IT in organizations, organizations in the natural environment, narrative and aesthetic perspectives on organizational phenomena, psychodynamics of group and intergroup behavior.

A. Hall-Phillips, Associate Professor; Ph.D., Purdue University; consumer behavior, business-to-business marketing, small business.

H. Higgins, Professor; Ph.D., Georgia State University; financial accounting, focusing on earnings expectation and international accounting.

F. Hoy, Beswick Professor of Entrepreneurship; Director, Collaborative for Entrepreneurship and Innovation; Ph.D., Texas A&M University; entrepreneurship, family and small business management, strategy, international entrepreneurship.

S. A. Johnson, Professor; Ph.D., Cornell University; lean process design, enterprise engineering, process analysis and modeling, reverse logistics.

C. Kasouf, Associate Professor; Ph.D., Syracuse University; product management, marketing strategy in fragmented industries, innovation management, marketing information use, strategic alliances.

R. Konrad, Assistant Professor; Ph.D., Purdue University; health systems engineering, patient flow optimization, health informatics, industrial engineering.

N. Kordzadeh, Assistant Professor; Ph.D., University of Texas at San Antonio; health informatics and analytics, social informatics and web 2.0, information privacy, applications of GIS in business and health care

D. Koutmos, Assistant Professor; Ph.D., University of Durham; finance, asset pricing, risk management.

E. Lingo, Assistant Professor; Ph.D., Harvard University; organizational studies, leadership, creativity.

E. T. Loiacono, Professor; Ph.D., University of Georgia; website quality, information system accessibility, e-commerce, affect in information systems.

K. Mendoza-Abarca, Assistant Professor; Ph.D., Kent State University; social entrepreneurship, international entrepreneurship, creativity and innovation.

F. Miller, Associate Professor; Ph.D., Michigan State University; managerial accounting and contracting in inter- and intra-firm relationships.

M. P. Rice, Professor; Ph.D., Rensselaer Polytechnic Institute; innovation, entrepreneurship, business development.

S. Saberi, Assistant Professor; Ph.D., University of Massachusetts-Amherst; operations, industrial engineering, supply chain management.

J. Schaufeld, Professor of Practice in Entrepreneurship; MBA, Northeastern University; entrepreneurship, technology commercialization, business acquisition and development.

P. Shah, Assistant Professor; Ph.D., Texas Tech University; marketing, brand strategy, product disposal strategy.

D. Strong, Professor; Ph.D., Carnegie-Mellon University; advanced information technologies, such as enterprise systems, and their use in organizations, MIS quality issues, with primary focus on data and information quality.

K. Sweeney, Professor of Practice; J.D., University of Wisconsin; finance.

S. Taylor, Professor; Ph.D., Boston College; aesthetics of organizational action.

W. Towner, Assistant Teaching Professor; Ph.D., Worcester Polytechnic Institute; operations management, lean manufacturing, six-sigma.

A. Trapp, Associate Professor; Ph.D., University of Pittsburgh; industrial engineering, combinatorial optimization, stochastic programming, operations research.

B. Tulu, Associate Professor; Ph.D., Claremont Graduate University; medical informatics, V.O.I.P., information security, telecommunications and networking, systems analysis and design.

H. G. Vassallo, Professor; Ph.D., Clark University; organizational behavior, project management, management of planned change, management of biotechnology, medical product liability.

E. V. Wilson, Associate Teaching Professor; Ph.D., University of Colorado; information systems, cognitive science.

S. A. Wulf, Professor of Practice; Ph.D., Columbia Pacific University; organizational behavior, leadership, business development, group dynamics.

A. Zeng, Assistant Dean and Professor; Ph.D., Pennsylvania State University; modeling and analysis of decisions in supply and/or distribution networks, applications of operations research and operations management techniques to supply chain process design and improvement, global supply chain management and international business.

J. Zhu, Professor; Ph.D., University of Massachusetts; information technology and productivity, e-business, performance evaluation and benchmarking.

Department Research

In addition to teaching, School of Business faculty are involved in a variety of sponsored research and consulting work. A sampling of current research includes: quality control in information-handling processes, supply chain management, decision/risk analysis, conflict management, capacity planning, international accounting differences, strategy and new venture teams, family and small business management, user experience, and health systems innovation.

The Collaborative for Entrepreneurship and Innovation

The Collaborative for Entrepreneurship and Innovation (CEI) is a university-wide program of the Robert A. Foisie School of Business, designed to inspire and nurture people to discover, create and commercialize new technology-based products, services and organizations. It coordinates all entrepreneurship-related activity at WPI, including graduate and undergraduate courses; a student-run entrepreneurship club; the Coleman Fellows program; and endowed competitions. Please call 508-831-5761 or email cei@wpi.edu for more information.

Programs of Study

The interaction between business and technology drives every aspect of our Graduate Business Programs. We believe the future of business lies in leveraging the power of technology to optimize business opportunities. WPI stays ahead of the curve, giving students the ability to combine sound strategies with cutting edge innovation, and the confidence to contribute meaningfully within a global competitive environment. The superior record of our graduates' successes highlight why WPI enjoys a nationally-recognized reputation as one of the most respected names in technology-based business education.

WPI offers a variety of graduate business programs focusing on the integration of business and technology. The Master of Business Administration (MBA) is a highly integrated, applications-oriented program that provides students with both the 'big picture' perspective required of successful upper-level managers and the hands-on knowledge needed to meet the daily demands in the workplace. WPI's focus on the management of technology comes from the recognition that rapidly changing technology is driving the pace of business.

Students enjoy extensive opportunities to expand their networks through associations with their peers and leading high-tech organizations. They also benefit from the latest available technologies and one of the nation's most wired universities. The program's strong emphasis on interpersonal and communications skills prepares students to be leaders in any organization, and the global threads throughout the curriculum ensure that students understand the global imperative facing all businesses. Whether dealing with information technology, biotechnology, financial markets, information security, supply chain management, manufacturing, or a host of other technology-oriented industries, the real world is part of the classroom, and students explore up-to-the-minute challenges faced by actual companies, through hands-on projects and teamwork. WPI promotes an active learning process, designed to develop the very best managers, leaders and executives in a technology-dependent world.

Graduate Certificates

Graduate business certificate are designed for technical and business professionals seeking focused, in-depth knowledge within a specific area of technology management. Certificates include: Health Systems Innovation; Information Security Management; Information Technology; Marketing Innovation; Supply Chain Analytics; and Supply Chain Essentials. Each certificate consists of 4 courses, which may be double-counted toward a related master's degree. Students may also customize their own graduate business certificate. For more information, please see http://business.wpi.edu/+certificates

Master of Business Administration (MBA)

WPI's MBA program features a set of ten core courses, designed to develop the skills managers need to develop business opportunities, analyze and improve business performance, and become leaders. In addition, the program includes two integrating project experiences: BUS 501, a course that challenges students to use the skills developed in the required core courses to make business decisions; and BUS 517 - the Capstone Graduate Qualifying project.

The following 7 required courses, should be completed before BUS 501:

- BUS 500 Business Law, Ethics and Social Responsibility
- FIN 500 Financial Information and Management
- FIN 501 Economics for Managers
- MIS 500 Innovating with Information Systems
- MKT 500 Marketing Management
- OBC 500 Group and Interpersonal Dynamics in Complex Organizations
- OIE 500 Analyzing and Designing Operations to Create Value

To complete the core requirements, students must also take the following 3 courses:

- ACC 503 Financial Intelligence for Strategic Decision-Making
- ETR 500 Entrepreneurship and Innovation
- OBC 501 Interpersonal and Leadership Skills

The MBA program culminates with a capstone Graduate Qualifying Project (BUS 517) which provides students with a hands-on, real-world opportunity to apply and enhance their classroom experience.

MBA students are required to complete 12 credit hours of free elective coursework. Elective concentration areas include:

- Entrepreneurship
- Information Security Management
- Information Technology
- Marketing
- Operations Management
- Process Design
- Supply Chain Management
- Sustainability
- Technological Innovation

MBA Options

Students may pursue the WPI MBA on a full- or part-time basis on our Worcester Campus or via a blended format that mixes online learning with 2 full-day on-campus face-to-face meetings per course per semester. Students join one of WPI's MBA Cohorts and may complete the MBA in 32 or 64 months with a defined group of their peers. For more information on MBA options, please see http://business.wpi.edu/+mba.

M.S. in Information Technology (MSIT)

The demand for knowledgeable IT professionals who understand business has never been greater. The MSIT program guarantees a solid foundation in information technology, with a wide range of cutting-edge concentrations, and the management principles critical to success in a technology-driven environment.

MSIT students must complete the following 5 required courses:

- MIS 500 Innovating with Information Systems
- MIS 571 Database Applications Development
- MIS 573 Systems Design and Development
- MIS 578 Telecommunications Management
- OBC 500 Group and Interpersonal Dynamics in Complex Organizations

MSIT students then must complete electives, distributed as follows:

- Choose 1 of the following:

  FIN 500 Financial Information and Management

  OBC 501 Interpersonal and Leadership Skills
- Choose 4 of the following:

  MIS 576 Project Management

  MIS 581 Information Technology Policy and Strategy

  MIS 582 Information Security Management

  MIS 583 User Experience Applications

  MIS 584 Business Intelligence
- Two free electives, which may include courses outside of business and a maximum of 3 credits of internship.

M.S. in Management (MSMG)

The MSMG offers students a flexible yet focused program that will improve business skills while excelling in technology-based organizations. The MSMG also provides a compelling pathway to an MBA, recognizing the value of work experience. Upon earning the MSMG, and after 2 – 6 years of professional experience, students may return to WPI to complete the requirements for an MBA with just 9 additional courses, including the hallmark project experience of WPI (MBA admission required).

- MSMG students complete the following 10 courses:
- BUS 500 Business Law, Ethics, and Social Responsibility
- FIN 500 Financial Information and Management
- FIN 501 Economics for Managers
- MIS 500 Innovating with Information Systems
- MKT 500 Marketing Management
- OBC 500 Group and Interpersonal Dynamics in Complex Organizations
- OIE 500 Analyzing and Designing Operations to Create Value
- 3 Electives

M.S. in Marketing and Innovation (MSMI)

A highly specialized program specifically designed for individuals employed in or aspiring to work in marketing positions and/or positions responsible for innovation within technology- oriented environments. The M.S. in marketing and innovation features 6 required courses including:

- ETR 500 Entrepreneurship and Innovation
- FIN 500 Financial Information and Management
- MKT 500 Marketing Management
- MKT 562 Marketing Research
- MKT 565 Digital Marketing
- OBC 500 Group and Interpersonal Dynamics in Complex Organizations

Students then select 4 electives from the following list:

- ETR 596 Selling and Sales
- MIS 583 User Experience Applications
- MKT 561 Consumer Behavior
- MKT 564 Global Technology Marketing
- MKT 567 Integrated Marketing Communications
- MKT 568 Data Mining Business Applications
- MKT 569 Product and Brand Management
- OIE 544 Supply Chain Analysis and Design

Students round out their MSMI with 2 free electives, which may include courses outside of business and a maximum of 3 credits of internship.

M.S. in Operations Analytics and Management (MSOAM)

Today's business environments deal constantly with changes requiring leadership for operational solutions. The MSOAM is a comprehensive Operations Management program that provides students with the ability to customize their program with a broad selection of electives focusing in-depth on issues in operations management and related business areas.

MSOAM students complete the following required courses:

- OBC 500 Group and Interpersonal Dynamics in Complex Organizations
- OIE 500 Analyzing and Designing Operations to Create Value
- OIE 541 Operations Risk Management
- OIE 544 Supply Chain Analysis and Design
- OIE 552 Modeling and Optimizing Processes
- OIE 554 Global Operations Strategy

Choose 1 *(the other may be used as an elective)*:

- MIS 500 Innovating with Information Systems
- MIS 571 Database Applications Development

Choose 1 *(the other may be used as an elective)*:

- OIE 555 Lean Process Design
- OIE 558 Designing and Managing Six-Sigma Processes

Students then select 4 electives from the following list:

- BUS 522 Global Business Experience
- BUS 546 Managing Technological Innovation
- BUS 597 Internship
- MIS 573 System Design and Development
- MIS 576 Project Management
- MIS 581 Information Technology Policy and Strategy
- MIS 582 Information Security Management
- MIS 583 User Experience Applications
- MIS 584 Business Intelligence

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- OBC 501 Interpersonal and Leadership Skills
- OBC 533 Negotiations
- OBC 536 Organizational Design
- OBC 537 Leading Change
- OIE 548 Productivity Management
- OIE 553 Global Purchasing and Logistics
- OIE 557 Service Operations Management

M.S. in Supply Chain Management (MSSCM)

Organizations in virtually every industry rely on intricate supply chains that globally manage goods and services demands. Synchronizing the flow of products, information, and funds is becoming increasingly complex with products that move across continents daily and deadlines that directly affect a company's profitability. This MSSCM program is designed to deliver an intensive analytical curriculum and to embrace various experiential learning opportunities to develop students' interdisciplinary skills necessary for developing career choices and leaderships in the field.

MSSCM students must complete the following 7 required courses:

- OIE 500: Analyzing and Designing Operations to Create Value
- OIE 544: Supply Chain Analysis and Design
- OIE 553: Global Purchasing and Logistics
- MIS 576: Project Management
- MKT 561: Consumer Behavior
- OBC 533: Negotiations
- OIE 597: Supply Chain Consulting Project

For those who have NOT taken finance or accounting as an undergraduate or elsewhere or who cannot demonstrate sufficient financial experience, choose 1 of the following:

- ACC 503: Financial Intelligence for Strategic Decision-Making
- FIN 500: Financial Information and Management
- OIE 598: Special Topic – Financial Analysis of Supply Chains

Students then select 4 electives from the following list:

- MKT 565: Digital Marketing
- MKT 568: Data Mining Business Applications
- OIE 541: Operations Risk Management
- OIE 559: Optimization Methods for Business Analytics
- OIE 598: Special Topic – Sustainable Supply Chain & Operations Management
- OIE 598: Special Topic – Materials Management in Supply Chains
- OIE 598: Special Topic – Supply Chain Simulation Modeling and Analysis
- BUS 598: Special Topic – Supply Chain Performance Analysis
- OIE 599: Supply Chain Research
- 1 course in other Business discipline or outside Business

Combined B.S./M.S. Program

This program is available to WPI undergraduate students wishing to combine one of the School of Business' four M.S. degrees with their B.S. A separate and complete application to the M.S. program must be submitted. Admission to the Combined Program is determined by the faculty of the School of Business. With careful planning both degrees may be completed within the student's four years of undergraduate study.

It is recommended that the M.S. application be submitted at the beginning of the student's junior year of undergraduate study. A student in the Combined Program continues to be registered as an undergraduate until the bachelor's degree is awarded.

To obtain a bachelor's degree via the Combined Program, the student must satisfy all requirements for the bachelor's degree, including distribution and project requirements.

To obtain an M.S. via the Combined Program, the student must satisfy all M.S. degree requirements.

Please refer to the section on the Combined Programs or contact the director of business programs for more information.

Admission Requirements

For the Master's program, applicants should have the analytic aptitude and academic preparation necessary to complete a technology-oriented business program. This includes a minimum of three semesters of college level math or two semesters of college level calculus. Applicants to the MSIT are also required to have a prior college-level programming course.

Applicants must have the earned equivalent of a four-year U.S. bachelor's degree to be considered for admission. Admission decisions are based upon all the information required from the applicant. GMAT or GRE required; waived for WPI students and alumni with a cumulative undergraduate GPA of 3.0+. Waivers may be considered based on work experience and/or advanced degrees.

For the Ph.D. an applicant must be a graduate of an accredited U.S. college or university or an approved foreign equivalent institution, and have earned a grade point average of 3.0 or better in all prior undergraduate and graduate studies. A student with a master's degree will be expected to have successfully demonstrated graduate level knowledge in a traditional business discipline such as Accounting, Finance, Marketing, Organizational Behavior, Entrepreneurship, Information Technology, or Operations Management; or in a discipline that is relevant to the student's proposed concentration. Additionally, the applicant will demonstrate undergraduate competency in Calculus, Statistics and/or Micro/Macro Economics.

Locations

Tailored to meet the challenges of working professionals, WPI offers full- and part-time graduate business study at our campus in Worcester, Massachusetts, as well as world-wide via our Blended courses.

Degree Requirements

For the M.B.A.

48 credits distributed as follows (credits in parentheses):

- **10 Core Courses**
  ACC 503, BUS 500, ETR 500, FIN 500, FIN 501, MIS 500, MKT 500, OBC 500, OBC 501, OIE 500 (30 credits)
- **Integrating Course**
  BUS 501 (3 credits)
- **Graduate Qualifying Project (GQP)**
  BUS 517 (3 credits)
- **4 Elective Courses** (12 credits)

For the M.S. in Information Technology (MSIT)

36 credits, distributed as follows (credits in parentheses):

- **5 Required Courses**
  MIS 500, MIS 571, MIS 573, MIS 578, OBC 500 (15 credits)
- **7 Electives Courses**
  1 of the following: FIN 500 or OBC 501 (3 credits)
  4 of the following: MIS 576, MIS 581, MIS 582, MIS 583, MIS 584 (12 credits)
- **2 Free Electives**, which may be any graduate course at WPI and a maximum of 3 credits of internship (6 credits)

For the M.S. in Management (MSMG)

30 credits, distributed as follows (credits in parentheses):

- **7 Required Courses**
  BUS 500, FIN 500, FIN 501, MIS 500, MKT 500, OBC 500, OIE 500 (21 credits)
- **3 Elective Courses**
  (9 credits)

For the M.S. in Marketing and Innovation (MSMI)

36 credits, distributed as follows (credits in parentheses):

- **6 Required Courses**
  ETR 500, FIN 500, MKT 500, MKT 562, MKT 565, OBC 500 (18 credits)
- **4 Elective Courses**
  Selected from the following:
  ETR 596, MIS 583, MKT 561, MKT 564, MKT 567, MKT 568, MKT 569, OIE 544 (12 credits)
- **2 Free Electives** which may be any graduate course at WPI and a maximum of 3 credits of internship (6 credits)

For the M.S. in Operations Analytics and Management (MSOAM)

36 credits, distributed as follows (credits in parentheses):

- **6 Required Courses**
  OBC 500, OIE 500, OIE 541, OIE 544, OIE 552, OIE 554 (18 credits)
- **Choose 1**
  MIS 500, MIS 571 (3 credits)
- **Choose 1**
  OIE 555, OIE 558 (3 credits)
- **4 Elective Courses**
  Selected from the following::
  BUS 222, BUS 546, BUS 597, MIS 573, MIS 576, MIS 581, MIS 582, MIS 583, MIS 584, OBC 501, OBC 533, OBC 536, OBC 537, OIE 548, OIE 553, OIE 557

For the M.S. in Supply Chain Management (MSSCM)

36 credits, distributed as follows (credits in parentheses):

- **7 Required Courses**
  OIE 500, OIE 544, OIE 553, MIS 576, MKT 561, OBC 533, SCM 598 (21 credits)
- **Choose 1**
  ACC 503, FIN 500, OIE 598 (3 credits)
- **Choose 4**
  BUS 598, MKT 565, MKT 568, OIE 541, OIE 559, OIE 598, SCM 599, 1 free elective (12 credits)

Ph.D. Program

The course of study leading to the Ph.D. degree in Business Administration requires the completion of 90 credits beyond the bachelor's degree, or 60 credits beyond the master's degree. For students proceeding directly from B.S. degree to Ph.D. degree, the 90 credits should be distributed as follows:

Coursework:	
Courses in B.A. (incl. Special Topics and ISP)	15 credits
Courses in or outside of B.A.	15 credits
Dissertation Research (BUS 699)	30 credits
Other:	30 credits
Additional coursework	
Additional Dissertation Research (BUS 699)	
Supplemental Research (BUS 698)	
TOTAL	**90 credits**

For students proceeding from master's to Ph.D. degree, the 60 credits should be distributed as follows:

Coursework:	
Courses in B.A. (incl. Special Topics and ISP)	12 credits
Dissertation Research (BUS 699)	30 credits
Other:	18 credits
Additional coursework	
Additional Dissertation Research (BUS 699)	
Supplemental Research (BUS 698)	
TOTAL	**60 credits**

In either case, the result of the dissertation research must be a completed doctoral dissertation. Only after admission to candidacy may a student receive credit toward dissertation research under *BUS 699*. Prior to admission to candidacy, a student may receive up to 18 credits of pre-dissertation research under *BUS 698*. All full-time students are required to register for the zero credit *BUS 691 Graduate Seminar* every semester.

Students formally accepted as a doctoral candidate must select a concentration in which to pursue their dissertation research. The available concentrations are listed below:

Entrepreneurship concentration: Entrepreneurship encompasses opportunity seeking and identification, financing new enterprises, corporate venturing and other related topics. Research subjects address the conceptualization of new venture business models through to formulating exit strategies. Special areas of emphasis include intellectual property commercialization, international and cross-cultural studies, and issues associated with transgenerational entrepreneurship in family business.

Information Technology concentration: Students will learn to use qualitative and quantitative methods to develop and apply theories regarding design, implementation, and use of advanced information systems and technologies with the goal of developing and publishing new Information Technology knowledge. Students will study information technology and how it affects individuals, organizations and society. By working closely with WPI's Information Technology scholars, students will learn to conduct theoretically sound Information Technology research that

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addresses real business problems, to apply for research grants, and to teach Information Technology courses. WPI's Information Technology scholars will involve Ph.D. candidates in their research activities in various organizations in the region, including those in the technology, healthcare, financial, and public sectors.

Operations Management concentration: Students will pursue research in the areas of management sciences, operations research, business analytics, health care management, supply chain management, and decision analysis. The operations area undertakes research on decision-making through quantitative modeling of operations functions in businesses. Research topics cover all levels of business decision-making, from operation systems design and technology choices to day-to-day scheduling and performance measurement. The program emphasizes research that focuses on real business problems and maintains a balance between theory and practice. This concentration is designed to train Ph.D. students in fundamental and applied business modeling and analytical thinking.

Academic Advising

Upon admission to the Doctoral Program, each student is assigned or may select a temporary advisor to arrange an academic Plan of Study covering the first 9 credits of study. This plan should be arranged before the first day of registration. Prior to registering for any additional credits, the student must identify a permanent dissertation advisor who assumes the role of academic advisor and with whom a suitable dissertation topic and the remaining Plan of Study are arranged. Prior to completing 18 credits, the student must form a dissertation committee that consists of the dissertation advisor, at least two other business administration faculty members, and at least one member from outside the student's area of concentration. These committee members should be selected because of their abilities to assist in the student's dissertation research.

The schedule of advising is as follows:

- Temporary advisor—meets with student prior to first registration to plan first 9 credits of study.
- Dissertation advisor—selected by student prior to registering for more than 9 credits.
- Program of study—arranged with dissertation advisor prior to registering for more than 9 credits.
- Dissertation committee—formed by student prior to registering for more than 18 credits. Consists of dissertation advisor, at least two B.A. faculty members, and at least one outside member.

This schedule ensures that students are well advised and actively engaged in their research at the early stages of their programs.

Admission to Candidacy

Admission to candidacy will be granted when the student has satisfactorily passed a written exam intended to measure fundamental ability in the area of concentration and at least one additional business discipline. The two areas are selected by the student. The exam is given in January. For students who enter the program with a bachelor's degree, the exam must be taken after three semesters if they began their studies in the fall, and after two semesters if they began in the spring. For students who enter the program with a master's degree, the exam must be taken after one semester if they began in the fall, and after two semesters if they began in the spring.

Students in a WPI M.S. program who plan to apply for fall admission to the Ph.D. program are strongly advised to take the candidacy exam in January before that fall. The details of the examination procedure can be obtained from the School of Business Graduate Policy and Curriculum Committee.

Dissertation Proposal

Each student must prepare a brief written proposal and make an oral presentation that demonstrates a sound understanding of the dissertation topic, the relevant literature, the techniques to be employed, the issues to be addressed, and the work done on the topic by the student to date. The proposal must be made within a year of admission to candidacy. Both the written and oral proposals are presented to the dissertation committee and a representative from the School of Business Graduate Policy and Curriculum Committee. The prepared portion of the oral presentation should not exceed 30 minutes, and up to 90 minutes should be allowed for discussion. If the dissertation committee and the graduate committee representative have concerns about either the substance of the proposal or the student's understanding of the topic, the student will have one month to prepare a second presentation that focuses on the areas of concern. This presentation will last 15 minutes with an additional 45 minutes allowed for discussion. Students can continue their research only if the proposal is approved.

Dissertation Defense

Each doctoral candidate is required to defend the originality, independence and quality of research during an oral dissertation defense that is administered by an examining committee that consists of the dissertation committee and a representative of the School of Business Graduate Policy and Curriculum Committee who is not on the dissertation committee. The defense is open to public participation and consists of a 45-minute presentation followed by a 45-minute open discussion. At least one week prior to the defense, each member of the examining committee must receive a copy of the dissertation. At the same time, an additional copy must be made available for members of the WPI community wishing to read the dissertation prior to the defense, and public notification of the defense must be given by the School of Business Graduate Policy and Curriculum Committee. The examining committee will determine the acceptability of the student's dissertation and oral performance. The dissertation advisor will determine the student's grade.

Course Descriptions

All courses are 3 credits unless otherwise noted.

ACC 503. Financial Intelligence for Strategic Decision-Making

This course builds on Financial Information and Management. It takes a managerial approach and combines publicly available and internal financial reports to help managers measure and manage firm performance. Accounting, economics, and psychology theories provide the framework for planning, evaluating performance, understanding moral hazard and how choices of what to measure affect behaviors and outcomes. The course will emphasize cost behaviors and the use of assumptions in the calculations of cost of goods sold and other significant revenue and expense accounts. Students will apply statistical methods to the analysis of cost behavior and the balanced scorecard.

BUS 500. Business Law, Ethics and Social Responsibility

This course combines analysis of the structure, function and development of the law most important to the conduct of business with an examination of the ethical and social context in which managers make decisions. Emphasizing the social responsibility considerations of all business stakeholders, the course focuses on practical applications via extensive use of case studies. Students will gain a sound understanding of the basic areas of U.S. and international law including: intellectual property law; business formation and organization; international business law; securities regulation; cyber law and e-commerce; antitrust law; employment law and environmental law.

BUS 501. Integrating Business Concepts to Lead Innovation

This course will be help students practice integration of the concepts learned in the core courses. There will be case studies, simulations and other activities emphasizing different aspects of business problems. These activities will challenge teams to provide innovative solutions. Important strategy theories and concepts will be discussed to help students integrate varying knowledge domains. (Prerequisites: FIN 500, BUS 500, FIN 501, MIS 500, MKT 500, OBC 500 and OIE 500 or equivalent content, or instructor consent)

BUS 517. Graduate Qualifying Project in Management (GQP)

This course integrates management theory and practice, and incorporates a number of skills and tools acquired in the M.B.A. curriculum. The medium is a major project, often for an external sponsor, that is completed individually or in teams. In addition to a written report, the project will be formally presented to members of the department, outside sponsors and other interested parties. (Prerequisites: ACC 503, BUS 500, BUS 501, ETR 500, FIN 500, FIN 501, MIS 500, MKT 500, OBC 500, OBC 501 and OIE 500 or equivalent content, or instructor consent)

BUS 522. Global Business Experience

Business is increasingly global. To be successful one must understand the customs and traditions of the regions in which they are operating. This course provides students with insight into different countries and business environments and includes an international trip where students will spend a week to 10 days on the ground in the featured region meeting with business, government and/or academic leaders; touring company sites; and learning about the region. Prior to the trip students will study business history, culture and current topics related to the featured region. Guest speakers will often be incorporated. Following the trip students will typically write reflective papers and deliver presentations.

BUS 546. Managing Technological Innovation

This course studies successful innovations and how firms must enhance their ability to develop and introduce new products and processes. The course will discuss a practical model of the dynamics of industrial innovation. Cases and examples will be discussed for products in which cost and product performance are commanding factors. The important interface among R&D/ manufacturing/marketing is discussed. International technology transfer and joint venture issues are also considered.

BUS 597. Internship

The internship is an elective-credit option designed to provide an opportunity to put into practice the principles that have been studied in previous courses. Internships will be tailored to the specific interests of the student. Each internship must be carried out in cooperation with a sponsoring organization, generally from off campus, and must be approved and advised by a WPI faculty member in the School of Business. Internships may be proposed by the student or by an off-campus sponsor. The internship must include proposal, design and documentation phases. Following the internship, the student will report on his or her internship activities in a mode outlined by the supervising faculty member. Students are limited to counting a maximum of 3 internship credits toward their degree requirements. Students must be making satisfactory academic progress as defined in the WPI graduate catalogue to be eligible to register for internship credit. International students who are working on a second U.S. master's degree and who have already used their master's-level Optional Practical Training (OPT) may petition the School of Business' Graduate Policy and Curriculum Committee to do additional Curricular Practical Training (CPT) beyond 3 credits on a non-credit basis. Part-time students cannot do an internship at their place of employment.

BUS 598. Independent Study

The student should have a well-developed proposal before approaching a faculty member about an independent study.

BUS 599. Thesis

(6 to 9 credits)

Research study at the master's level.

BUS 691. Graduate Seminar

(0 credits)

Seminars on current issues related to entrepreneurship, information technology and operations management are presented by authorities in their fields. All full-time Ph.D. students in Business Administration are required to register and attend.

BUS 697. Independent Study

(1-3 credits)

For Ph.D. students wishing to conduct independent study on special topics related to their concentration. (Prerequisite: Consent of research advisor)

BUS 698. Directed Research

(Credits TBD)

For Ph.D. students wishing to gain research experience peripheral to their thesis topic. (Prerequisite: Consent of research advisor)

BUS 699. Dissertation Research

(Credits TBD)

Intended for Ph.D. students admitted to candidacy wishing to obtain research credit toward their dissertations. (Prerequisite: Consent of research advisor)

ETR 500. Entrepreneurship and Innovation

Entrepreneurship involves many activities, including identifying and exploiting opportunities, creating and launching new ventures, introducing new products and new services to new markets. It is based on implementing innovations within existing organizations and creating new opportunities. This course is intended to introduce students to entrepreneurial thinking and methods of executing their ideas. Topics include recognizing and evaluating opportunities, forming new venture teams, preparing business and technology commercialization plans, obtaining resources, identifying execution action scenarios, and developing exit strategies.

ETR 593. Technology Commercialization: Theory, Strategy and Practice

In the modern world of global competition the ability to utilize technological innovation is increasingly important. This course will examine the sources of new technology, the tools to evaluate new technologies, the process of intellectual property transfer, and the eventual positioning of the resultant products and services in the commercial market. Its purpose is to improve the probability of success of this discipline in both existing organizational models and early stage ventures. Specific cases studies of successful technology commercialization processes will be used to supplement the course materials.

ETR 596. Selling and Sales

Selling is a major part of our business and professional lives. This is especially important for those who are launching new ventures. Business propositions need to be presented to (and need to be sold to) potential investors, employees, colleagues, and certainly potential employers. Later there is a need to sell products or services to customers. Common to all is a sales process and organization model that can be developed that is focused on meeting customer and other stakeholder needs through effective selling disciplines.

FIN 500. Financial Information and Management

This course develops expertise in financial decision-making by focusing on frequently used financial accounting information and the conceptual framework for managing financial problems. Students are introduced to the accounting and financial concepts, principles and methods for preparing, analyzing and evaluating financial information, for the purpose of managing financial resources of a business enterprise and investment decisions. The course adopts a decision-maker perspective by emphasizing the relations among financial data, their underlying economic events, corporate finance issues, and the responses by market participants.

FIN 501. Economics for Managers

This course covers fundamental microeconomic and macroeconomic theories to help managers formulate effective business decisions. Current events are used in addition to economic theories to explain the concepts of the market system, gains from trade, supply and demand, consumer behavior, firm behavior, market structure, long-run economic growth, economic cycle, financial system, monetary policy, and fiscal policy. Students will complete a "Market Watch" project to learn to explain and predict changes in macroeconomic indicators, including gross domestic product, interest rates, global stock indices, commodity prices and foreign exchange rates.

FIN 521. Financial Management in a Global Environment

This course builds from Financial Information and Management, and extends closed-economy financial management to the international market environment. Drawing from theories based on culture, corporate finance, and investor protection laws, this course examines differences in corporate governance, financial information, and financial markets in global settings. The first focus is on accountability of financial resources, the implications of globalization on firms' financial reporting and decision-making. The second focus is on international markets and institutions, how the access and exposure to different market environments can affect the firm's financial and investment decisions. Major topics include the relationship between foreign exchange and other financial variables; measurement and management of the exchange risk exposure of the firm; international investment decisions by firms and investors; and financing the global operations of firms. (Prerequisite: FIN 500 or equivalent content, or consent of instructor)

FIN 598. Special Topics

MIS 500. Innovating with Information Systems

This course focuses on information technology and innovation. Topics covered are information technology and organizations, information technology and individuals (privacy, ethics, job security, job changes), information technology and information security, information technology within the organization (technology introduction and implementation), business process engineering and information technology between organizations (electronic data interchange and electronic commerce).This course provides the knowledge and skills to utilize existing and emerging information technology innovatively to create business opportunities.

MIS 571. Database Applications Development

Business applications are increasingly centered on databases and the delivery of high-quality data throughout the organization. This course introduces students to the theory and practice of computer-based data management. It focuses on the design of database applications that will meet the needs of an organization and its managers. The course also covers data security, data integrity, data quality, and backup and recovery procedures. Students will be exposed to commercially available database management systems, such as MS/Access and Oracle. As a project during the course, students will design and implement a small database that meets the needs of some real-world business data application. The project report will include recommendations for ensuring security, integrity, and quality of the data.

MIS 573. System Design and Development

This course introduces students to the concepts and principles of systems analysis and design. It covers all aspects of the systems development life cycle from project identification through project planning and management, requirements identification and specification, process and data modeling, system architecture and security, interface design, and implementation and change management. Object-oriented analysis techniques are introduced. Students will learn to use an upper level CASE (computer-aided software engineering) tool, which will be employed in completing a real-world systems analysis and design project. (Prerequisite: MIS 571 or equivalent content, or instructor consent)

MIS 576. Project Management

This course presents the specific concepts, techniques and tools for managing projects effectively. The role of the project manager as team leader is examined, together with important techniques for controlling cost, schedules and performance parameters. Lectures, case studies and projects are combined to develop skills needed by project managers in today's environment.

MIS 578. Telecommunications Management

This course provides students with the technical and managerial background for developing and managing an organization's telecommunications infrastructure. On the technical side, it covers the fundamentals of data transmission, local area networks, local internetworking and enterprise internetworking, and security. Coverage includes data communications and computer networking; local area communications topics such as cabling, and local area network hardware and software; and topics involved in wide area networking, such as circuit and packet switching, and multiplexing. On the managerial side, this course focuses on understanding the industry players and key organizations, and the telecommunications investment decisions in a business environment. Coverage includes issues in the national and international legal and regulatory environments for telecommunications services.

MIS 581. Information Technology Policy and Strategy

Fast-paced changes in technology require successful IS managers to quickly understand, adapt, and apply technology when appropriate. They must recognize the implications new technologies have on their employees and the organization as a whole. In particular, they must appreciate the internal (e.g., political and organizational culture) and external (e.g., laws, global concerns, and cultural issues) environments that these changes occur within and plan accordingly. This course focuses on the core IS capabilities that IS managers must consider when managing technology within their organization: business and IT vision, design of IT architecture, and IT service delivery. This course will build on the knowledge and skills gained from previous MIS courses. (Prerequisite: MIS500 or equivalent content, or instructor consent)

MIS 582. Information Security Management

This course introduces students to the fundamentals of Information Security Management. It is designed to develop in students an understanding of and appreciation for the importance of information security to all enterprises, and to enable current and future managers to understand the important role that they must play in securing the enterprise. This course is appropriate for any student interested in gaining a managerial-level understanding of information security. A combination of readings, lectures, case studies, guest speakers, and discussion of real world events will be used to bridge the gap between theory and practice. The course will primarily explore the Common Body of Knowledge (CBK) of information security, along with other related topics. It will also explore the interaction between People, Process and Technology as the cornerstone of any effective information security program. Upon completion of this course, the student will have an in-depth understanding of the essential components of a comprehensive information security program, as well as an understanding of the technology at work behind the scenes.

MIS 583. User Experience Applications

The course provides an introduction to various methods to study user experience, which includes the newest research in user experience theory and practice (e.g., the use of eye tracking in informing the design of webpages). Students will learn how businesses can benefit from user experience research to develop new or improve existing products and services. Both theoretical concepts and practical skills will be addressed within the scope of the class through hands-on projects and assignments. (Recommended background: ability to program in a higher level programming language)

MIS 584. Business Intelligence

Today's business computing infrastructures are producing the large volumes of data organizations need to make better plans and decisions. This course provides an introduction to the technologies and techniques for organizing and analyzing data about business operations in a way that creates business value, and prepares students to be knowledgeable producers and consumers of business intelligence. During the course, students will study a variety of business decisions that can be improved by analyzing large volumes of data about customers, sales, operations, and business performance. Students will apply commercially available business intelligence software to analyze data sets and make recommendations based on the results. The course explores the technical challenges of organizing data for analysis and the managerial challenges of creating and deploying business intelligence expertise in organizations. The course includes business cases, in-class discussion, and hands-on analyses of business data. It is designed for any student interested in analyzing data to support business decision making, including students whose primary focus is IT, Marketing, Operations, or Business Management. (Prerequisite: MIS 571 or CS 542, or equivalent content, or consent of the instructor.)

MKT 500. Marketing Management

This course addresses consumer and industrial decision-making, with emphasis on the development of products and services that meet customer needs. Topics covered include management and the development of distinctive competence, segmentation and target marketing, market research, competitor analysis and marketing information systems, product management, promotion, price strategy, and channel management. Students will learn how the elements of marketing strategy are combined in a marketing plan, and the challenges associated with managing products and services over the life cycle, including strategy modification and market exit.

MKT 561. Consumer Behavior

This course provides an in-depth analysis of factors that affect purchase decisions and consumption in the marketplace. Topics covered include consumer behavior theory, an examination of attitude formation and value creation, the challenges of consumer protection, market research, and the influence of technology on consumer decision making. Students will learn how the elements of consumer behavior impact marketing strategy and decisions through case analysis and other activities

MKT 562. Marketing Research

This course is designed to equip students with research methods and tools that are used for marketing decision making. Students will learn to conduct, use, apply, interpret, and present marketing research in order to become effective decision makers. The topics covered in this course include problem formulation, research design, data collection methods, and finally presentation of a research plan. This course will be an activity-based course involving design and presentation of a marketing research plan. Basic knowledge of marketing concepts is assumed. (Prerequisite: MKT 500 or equivalent content, or consent of instructor.)

MKT 564. Global Technology Marketing

Extending technology to global markets requires an understanding of consumer behavior in different cultures, and effective management of risk and overseas infrastructures. This course addresses the issues associated with technology application in new markets and includes the following topics: consumer behavior differences in international markets and the implications for the marketing mix, cultural differences that affect business practices in new markets, managing exchange rate fluctuation, factors that affect manufacturing and research location, the impact of local government on marketing decision making, and the use of strategic alliances to acquire expertise and manage risk in global market development. Knowledge of marketing management is assumed.

MKT 565. Digital Marketing

The rapid evolution of technology has led to increasingly well-informed buyers who are connected, communicative, and more in control than ever. This course discusses the theory and practice of digital marketing and its role in building relationships and, ultimately, driving sales. It examines digital technologies and their impact on business models, the marketing mix, branding, communication strategies, and distribution channels. Emphasis is placed on contemporary topics that face today's marketing managers -- including online lead generation, search, social networking, and ecommerce -- and their application within a comprehensive, integrated digital marketing strategy. The course considers the opportunities and challenges faced in business-to-consumer and business-to-business markets. It covers latest research, current practices, and hands-on project work. (Prerequisite: MKT 500 or equivalent content, or consent of instructor.)

MKT 567. Integrated Marketing Communications

This course provides students with an understanding of the role of integrated marketing communications in the overall marketing program and its contribution to marketing strategy. The tools of marketing communications include advertising, sales promotion, publicity, personal selling, public relations, trade shows, direct, and online marketing. Understanding the concepts and processes that organizations use in developing effective and synergistic marketing communications is useful for managers across functional disciplines. This course will also consider ethical issues of IMC.

MKT 568. Data Mining Business Applications

This course provides students with the key concepts and tools to turn raw data into useful business intelligence. A broad spectrum of business situations will be considered for which the tools of classical statistics and modern data mining have proven their usefulness. Problems considered will include such standard marketing research activities as customer segmentation and customer preference as well as more recent issues in credit scoring, churn management and fraud detection. Roughly half the class time will be devoted to discussions on business situations, data mining techniques, their application and their usage. The remaining time will comprise an applications laboratory in which these concepts and techniques are used and interpreted to solve realistic business problems. Some knowledge of basic marketing principles and basic data analysis is assumed.

MKT 569. Product and Brand Management

The conversion of technology into new products requires an understanding of how to develop a meaningful value proposition and integrate the development of a product with a marketing strategy that creates brand equity. This course will focus on the management of products, the implications of other marketing decisions on product and brand management, the management of product lines within the organization, including introduction, growth, and market exit. (Prerequisite: MKT 500 or equivalent content, or consent of instructor.)

MKT 598. Special Topics

OBC 500. Group and Interpersonal Dynamics in Complex Organizations

This practice-based course simulates a complex organization with critical interdependencies at interpersonal, group, and intergroup levels. Students will be asked to make sense of their experiences through class discussions, individual reflection and readings in organization studies. This course is intended to be a student's first course in organizational studies.

OBC 501. Interpersonal and Leadership Skills

This course considers effective interpersonal and leadership behaviors in technological organizations. Course material focuses on understanding, changing and improving our behaviors and those of others by examining our own practices and analyzing examples of leadership behaviors. The course also considers interpersonal and leadership behaviors in relation to teams, cultural diversity, and ethics in organizations. Assignments may include personal experiments, case analyses, individual and group projects and/or presentations. (Prerequisite: OBC 500 or equivalent content, or instructor consent)

OBC 533. Negotiations

This course focuses on improving the student¹s understanding of the negotiation process and effectiveness as a negotiator. Emphasizes issues related to negotiating within and on behalf of organizations, the role of third parties, the sources of power within negotiation, and the impact of gender, culture and other differences. Conducted in workshop format, combining theory and practice.

OBC 535. Managing Creativity in Knowledge Intensive Organizations

This course considers creativity in its broadest sense from designing new products and processes to creating our own role and identity as managers and leaders in knowledge-intensive organizations. In this course we will look actively at our own creative process and how we might more fully realize our creative potential. At the same time we will build a conceptual understanding of creating, creativity, and knowledge based in the philosophic, academic, and practitioner literatures. We will critically apply this conceptual understanding to organizational examples of managing creativity in support of practical action.

OBC 536. Organizational Design

A key role for organizational leaders is to design their organization to achieve their desired results. This course applies design thinking and methods to the practical problems of designing various sized organizations for optimal results in a complex environment. This is based on a foundation of organizational theory, design methodology, and organizational strategy. (Prerequisite: OBC 500 or equivalent content, or instructor consent)

OBC 537. Leading Change

This course focuses on the role of leadership in the design and implementation of organizational change. Topics include visioning, communication, social influence, power, resiliency, and resistance to change. Teaching methods include classroom discussion of readings and cases, simulations, and experiential exercises. (Prerequisite: OBC 500 or equivalent content, or instructor consent)

OIE 500. Analyzing and Designing Operations to Create Value

The operations of an organization focus on the transformation processes used to produce goods or provide services. In this course, a variety of statistical and analytical techniques are used to develop deep understanding of process behavior, and to use this analysis to inform process and operational designs. Topics such as measures of dispersion and confidence descriptions, correlation and regression analysis, and time series mathematics will be explored. Operations design is driven by strategic values, and can be critical to developing and sustaining competitive value. Philosophies such as lean thinking, as well as technology-based techniques such as optimization and simulation, are explored as a means of developing robust and effective operations.

OIE 541. Operations Risk Management

Operations risk management deals with decision making under uncertainty. It is interdisciplinary, drawing upon management science and managerial decision-making, along with material from negotiation and cognitive psychology. Classic methods from decision analysis are first covered and then applied, from the perspective of business process improvement, to a broad set of applications in operations risk management and design including: quality assurance, supply chains, information security, fire protection engineering, environmental management, projects and new products. A course project is required (and chosen by the student according to his/her interest) to develop skills in integrating subjective and objective information in modeling and evaluating risk. (An introductory understanding of statistics is assumed.)

OIE 544. Supply Chain Analysis and Design

This course studies the decisions and strategies in designing and managing supply chains. Concepts, techniques, and frameworks for better supply chain performance are discussed, and how e-commerce enables companies to be more efficient and flexible in their internal and external operations are explored. The major content of the course is divided into three modules: supply chain integration, supply chain decisions, and supply chain management and control tools. A variety of instructional tools including lectures, case discussions, guest speakers, games, videos, and group projects and presentations are employed. (Prerequisite: OIE 500 or equivalent content, or instructor consent)

OIE 548. Productivity Management

Productivity management and analysis techniques and applications are covered from engineering and management perspectives. Topics include benchmarking, production functions, and the concept of relative efficiency and its measurement by data envelopment analysis. Application examples include efficiency evaluations of bank branches, sales outlets, hospitals, schools and others. (Prerequisite: OIE 500, or equivalent content, or consent of the instructor.)

OIE 552. Modeling and Optimizing Processes

This course is designed to provide students with a variety of quantitative tools and techniques useful in modeling, evaluating and optimizing operation processes. Students are oriented toward the creation and use of spreadsheet models to support decision-making in industry and business.

OIE 553. Global Purchasing and Logistics

This course aims to develop an in-depth understanding of the decisions and challenges related to the design and implementation of a firm's purchasing strategy within a context of an integrated, global supply chain. Topics centering on operational purchasing, strategic sourcing, and strategic cost management will be covered. The global logistics systems that support the purchasing process will be analyzed, and the commonly used techniques for designing and evaluating an effective logistics network will be studied.

OIE 554. Global Operations Strategy

This course focuses on operations strategy from a global perspective. Topics such as strategy of logistics and decisions to outsource are examined. As an example, the strategic issues concerned with firms that are doing R&D in the United States, circuit board assembly in Ireland and final assembly in Singapore. Cases, textbooks and recent articles relating to the topic are all used. Term paper based on actual cases is required.

OIE 555. Lean Process Design

Lean thinking has transformed the way that organizational processes are designed and operated, using a systematic approach that eliminates waste by creating flow dictated by customer pull. In this course we explore the lean concepts of value, flow, demand-pull, and perfection in global, multistage processes. The tactics that are used to translate these general principles into practice, such as creating manufacturing cells, are also discussed. The design process is complicated because in reality not all wastes can be eliminated. To learn effective design, students will practice applying lean ideas in case studies and simulations, exploring how variability affects process dynamics and combining this knowledge with analysis of process data.

OIE 557. Service Operations Management

Successful management of service organizations often differs from that of manufacturing organizations. Service business efficiency is sometimes difficult to evaluate because it is often hard to determine the efficient amount of resources required to produce service outputs. This course introduces students to the available techniques used to evaluate operating efficiency and effectiveness in the service sector. The course covers key service business principles. Students gain an understanding of how to successfully manage service operations through a series of case studies on various service industries and covering applications in yield management, inventory control, waiting time management, project management, site selection, performance evaluation and scoring systems. The course assumes some familiarity with basic probability and statistics through regression.

OIE 558. Designing and Managing Six-Sigma Processes

This course teaches Six-Sigma as an organizational quality system and a set of statistical tools that have helped the world's leading companies save millions of dollars and improve customer satisfaction. This course is organized in three parts: part one covers the essentials of Six-Sigma, including fundamental concepts, the advantages of Six-Sigma over Total Quality Management, and a five-phase model for building a Six-Sigma organization; part two of the course covers the Six-Sigma training, including technical topics such as capability and experimental design as well as how to train "Black Belts" and other key roles; part three describes the major activities of the Six-Sigma Roadmap, from identifying core processes to executing improvement projects to sustaining Six-Sigma gains.

OIE 559. Optimization Methods for Business Analytics

This course covers mathematical optimization in greater detail beyond the foundational concepts of linear programming. A variety of optimization problem classes will be addressed, likely including integer programming, nonlinear programming, stochastic programming and global optimization. While ensuring an appropriate level of theory, the main emphasis will be the methodological and computational aspects of solving such problems arising in the operational, manufacturing, and service sectors. Recommended background: Previous course(s) in linear algebra, basic knowledge about optimization and linear programming, or consent of the instructor.

OIE 597. Supply Chain Consulting Project

This course integrates Supply Chain Management theory and practice, and incorporates a number of skills and tools acquired in the Supply Chain Management curriculum. The objective of this course is twofold: (1) to enrich students' experiential learning and equip the students with additional skillsets and capabilities to tackle real-world problems; and (2) to enhance their teamwork, interpersonal and consulting skills. The media is a consulting project, to be sponsored by an external organization, and is completed in teams. In addition to a written report, the project will be formally presented to members of the School, outside sponsors and other interested parties. Prerequisites: OIE 500, OIE 544, OIE 553, MIS 576, MKT 561, and OBC 533 or equivalent content, or instructor consent.

OIE 598. Special Topics

OIE 599. Supply Chain Research

This research study is at the master's level. The course provides a research experience for students interested in studying a pressing supply chain management problem or challenge. Students must satisfactorily complete a written paper and are encouraged to publically present the results.

Chemical Engineering

Faculty

S. C. Roberts, Professor and Department Head; Ph.D., Cornell University. Cellular engineering, plant cell culture, biotechnology, metabolic pathway engineering

T. A. Camesano, Professor; Ph.D., Pennsylvania State University. Bacterial adhesion and interaction forces, biopolymers, bacterial/natural organic matter interactions

W. M. Clark, Associate Professor and Associate Department Head; Ph.D., Rice University. Separations, bioseparation, two-phase electrophoresis, filtration using inorganic membranes

R. Datta, Professor; Ph.D., University of California, Santa Barbara. Catalysis and reaction engineering as applied to fuel cells and hydrogen

N. A. Deskins, Associate Professor; Ph.D., Purdue University. Energy production, nanomaterials research and development, pollution control and abatement, catalysis and chemical kinetics, and computational chemistry

D. DiBiasio, Associate Professor; Ph.D., Purdue University. Engineering education, teaching and learning, assessment

A. G. Dixon, Professor; Ph.D., University of Edinburgh. Transport in chemical reactors, applications of CFD to catalyst and reactor design, membrane separation and reactors

N. K. Kazantzis, Professor; Ph.D., University of Michigan. Techno-economic performance analysis, sustainable design and control of chemical processes, energy production and environmental systems, valuation methods for clean energy technology options in the presence of uncertainty, process safety and chemical risk analysis

S. J. Kmiotek, Professor of Practice, Ph.D., Worcester Polytechnic Institute. Chemical process safety, air pollution control, pollution prevention

A. M. Peterson, Assistant Professor, Ph.D., Drexel University. Biomaterials, multifunctional smart materials, polymer films and interfaces

E. J. Stewart, Assistant Professor, Ph.D., University of Michigan. Biological soft matter, bacterial biofilms, biophysics of host-pathogen interactions, complex fluids, microfluidics.

A. R. Teixeira, Assistant Professor; Ph.D., University of Massachusetts Amherst. Reaction engineering, heterogeneous catalysis, microfluidic crystallization

M. T. Timko, Assistant Professor, Ph.D., MIT. Renewable energy, liquid and biomass fuels, reaction engineering, fuel refining and desulfurization

E. M. Young, Assistant Professor; Ph.D., University of Texas at Austin. Synthetic biology, metabolic pathway engineering, yeast gene expression, transport protein engineering

H. S. Zhou, Associate Professor; Ph.D., University of California-Irvine. Bioanotechnology, bioseparations, micro- and nano-bioelectronics, bioMEMS, microfluidics, polymer thin films, surface modification, microelectronic and photonic packaging

W. P. Zurawsky, Associate Teaching Professor; Ph.D., University of Illinois. Membrane permeation and separations, plasma processing.

Emeritus

Y. H. Ma, Professor Emeritus; Ph.D., Massachusetts Institute of Technology

W. R. Moser, Professor Emeritus; Ph.D., Massachusetts Institute of Technology

R. W. Thompson, Professor Emeritus; Ph.D., Iowa State University

A. H. Weiss, Professor Emeritus; Ph.D., University of Pennsylvania

Research Interests

The Chemical Engineering Department's research efforts are concentrated in the following major areas: bioengineering, advanced functional materials, clean energy development and computational science and engineering.

Bioengineering research focuses on biomaterials, cell-surface interactions, cellular engineering, metabolic engineering and synthetic biology. Advanced functional materials research focuses on advanced carbon materials, nano-sensors, polymers and structural composite materials. Clean energy development research focuses on biomass conversion, resource and energy efficiency, catalysis, fuel cells, reaction engineering, solar energy and zeolite synthesis. Computational science and engineering research focuses on computational fluid dynamics, genome scale modeling, molecular modeling, process systems analyses and reactor design.

Master's and doctoral candidates' research in each of these areas involves the application of fundamental aspects of chemical engineering to interdisciplinary, societally relevant problems. Studies may be pursued in the following areas:

Bacterial Adhesion to Biomaterials

The mechanisms governing bacterial adhesion to biomaterials, including catheters and other implanted devices, are poorly understood; however, it is known that the presence of a biofilm on a biomaterial surface will lead to infection and cause an implanted device to fail. Research is aimed at characterizing bacterial interaction forces and adhesion to biomaterials, and developing anti-bacterial coatings for biomaterials. We are using novel techniques based on atomic force microscopy (AFM) to quantify the nanoscale adhesion forces between bacteria and surfaces.

Catalyst and Reaction Engineering

Research in this area is centered on the physical and chemical behavior of fluids, especially gases, in contact with homogeneous and heterogeneous catalysts as well as ways to improve organic and inorganic crystal growth. Projects include diffusion through porous solids, multicomponent adsorption, mechanism studies, microkinetics, reaction networks, synthesis and characterization of catalysts, catalytic reformers, electrochemical

synthesis, heat and mass transfer in catalytic reactors, and simulation of catalyst surfaces and reaction sites. Experimental techniques include standard lab-scale reactors, microreactors, and in situ spectroscopic instruments to monitor chemical reactions. Applications include partial oxidation reactions, steam reforming to produce hydrogen, pharmaceuticals synthesis and conversion of bio-renewable feeds into commodity chemicals.

Fuel Cell and Battery Technology

Fuel cells have potential as clean and efficient power sources for automobiles and stationary applications. Research is being conducted on developing, characterizing and modeling of fuel cells that are robust for these consumer applications and includes development of CO-tolerant anodes, higher temperature proton-exchange membranes and direct methanol fuel cells. Ongoing research also includes reformers and membranes for production of hydrogen from liquid fuels, flow batteries for grid energy storage and fuel cells for electrochemical synthesis and reforming processes.

Functional Polymer Surfaces and Interfaces

Studies on the processing-structure-property relationships in polymers and polymer composites, with a focus on interfacial phenomena in layer-by-layer systems (polyelectrolyte and additive manufacturing), are performed. Our goal is to use assembly conditions, instead of complex chemistries, to modulate both bulk and nano-scale properties and function. Our approach is unique in that we tackle similar types of problems in systems assembled on drastically different length and time scales; hence, our work considers the relevant physics and chemistries from multiple perspectives. The research activities can be divided into four main thrusts: processing-structure relationships in polyelectrolyte complexes (PECs), growth factor (GF) release from PEMs, investigation of interfaces in additively manufactured (AM) polymer structures, and thermal modeling of AM process.

Lab-on-chip and BioMEMS

Research in the area of lab-on-chip and BioMEMS involves developing a fundamental understanding of microfluidics transport and surface reaction kinetics in the micro-and nano-domains to design and fabricate chip-based bioseparation and biosensing devices and application of bionanotechnology for rapid and sensitive molecular diagnostics. Novel nanomaterials for biomedical applications are also of interest.

Metabolic and Cellular Engineering

The goal of this research is to engineer advanced "cell factories". To accomplish this goal, researchers look to control gene expression, metabolism and protein function by writing new DNA sequences into genomes. Whether to understand fundamental questions about genetics, or to modify cells to produce valuable medicines and fuels, engineering DNA is an interdisciplinary challenge. Techniques such as next-generation sequencing, modeling, molecular biology and flow cytometry are used.

Molecular Modeling of Materials for Sustainability

Computer technologies have advanced to the point of being able to accurately determine properties of material and chemical systems. For example, catalysts involve a number of reactions that are difficult to determine using experimental techniques. Research is being conducted in the areas of photocatalysis, photovoltaics, industrial catalysis, and environmental catalysis, all with the goal of producing environmentally-safe energy and chemicals. Sample projects include determining active catalysts for CO2 photo-reduction to solar fuels, simulating alloys for fuel cells, and modeling carbon-based materials.

Plant Cell Biotechnology

Plant cells synthesize an array of sophisticated "specialized metabolites" that serve a variety of functions as human health agents, colors, flavoring and agricultural chemicals. Production of these compounds for clinical or industrial supply can be challenging due to their low yields in nature, under-defined metabolic pathways and difficult gene transformation technologies. Plant cell culture technology can be exploited not only to synthesize these valuable compounds, but also to gain fundamental insights into regulation of plant cell metabolism so that systems can be effectively engineered. By considering all scales of cellular engineering – intra, inter and extra, cultures can be designed to produce yield yields of desirable molecules.

Reactor modeling and simulation

A better understanding of interactions between reactor transport processes and chemical reaction is needed to improve reactor efficiency, which contributes to sustainable engineering. Multiscale approaches are used to give new insight into the development of catalysts and reactors, such as computational fluid dynamics (CFD) and multiphysics methods, for example microkinetics and multicomponent diffusion models can be integrated into the CFD simulations of fixed bed reactors. Applications include partial oxidation reactions, and steam reforming for generation of hydrogen and synthesis gas, one route towards the generation of clean power. Other research includes study of membrane modules for recovery of high-purity hydrogen, membrane reactors for process intensification of hydrogen generation, and new catalytic materials such as ceramic foams.

Sustainable Fuels

Transportation and shipping rely on access to affordable and abundant supplies of liquid fuels. Research is being conducted to deliver these liquid fuels in more sustainable ways, for example, using green technologies, waste feeds, and renewable feeds. The primary research tools include catalysis science, reactor design, computational modeling, and metabolic engineering. Breaking down lignocellulosic bio-polymers is one of the main technical and economic barriers preventing affordable production of biomass-derived fuels. New techniques and technologies are being developed to understand and control the de-polymerization processes. Fermentation of the resulting simple sugars is an effective method to produce hydrocarbon fuels. Here, work is on-going to develop fermenter technologies that produce drop-in biofuels, such as butanol. With conventional oil reserves dwindling, environmentally responsible upgrading of heavy oils is becoming increasingly important. Research into green

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technologies which reduce the energy footprint of heavy oil upgrading are being studied. Waste plastics represent an energy dense feed that is currently under-utilized. Work is ongoing to convert waste plastics into high-value monomers and liquid fuels. Likewise, food wastes are a low-cost and energy dense feedstock being studied for potential production of liquid fuels. Lastly, many of these processes co-produce a solid char material which reduces the energy yield of the oil product. Studies are ongoing to valorize these char products as waste water treatment sorbents and in other applications.

Techno-economic performance analysis, sustainable design, control and safety of chemical processes and energy systems

Current research efforts lie in the broader areas of nonlinear process techno-economic performance analysis, sustainable design, control and safety. In particular, the following thematic areas may be identified in our current research efforts: (1) Techno-economic performance assessment and technology valuation methods in the presence of uncertainty; (2) synthesis of robust digital feedback regulators for nonlinear processes; (3) design of state estimators for digital process performance monitoring and fault detection/ diagnosis purposes; (4) chemical risk assessment and management with applications to process safety; (5) development of the appropriate software tools for the effective digital implementation of the above process analysis, control, performance monitoring and risk assessment schemes

Zeolite Science and Technology

Research in the area of zeolite science is driven by the need to establish an underlying understanding of the complex phenomena driving the synthesis and applications of molecular sieve zeolites. In particular, utilizing core reaction engineering techniques to elucidate the fundamental mechanisms of zeolite nucleation and crystal growth in hydrothermal systems is of interest. Uses of zeolites as liquid and gas phase adsorbents, and as catalysts, are being studied. Incorporation of zeolites into membranes for separations is being investigated due to zeolites' very regular pore dimensions on the molecular level.

Programs of Study

Students have the opportunity to do creative work on state-of-the-art research projects as a part of their graduate study in chemical engineering. The program offers excellent preparation for rewarding careers in research, industry or education. Selection of graduate courses and thesis project is made with the aid of a faculty advisor with whom the student works closely. All graduate students participate in a seminar during each term of residence.

The master's degree program in chemical engineering is concerned with the advanced topics of the field. While specialization is possible, most students are urged to advance their knowledge along a broad front. All students select a portion of their studies from core courses in mathematics, thermodynamics, reactor design, kinetics and catalysis, and transport phenomena. In addition, they choose courses from a wide range of elective. While a master's degree can be obtained with coursework alone, most students carry on research terminating in a thesis.

In the doctoral program, a broad knowledge of chemical engineering topics is required for success in the qualifying examination. Beyond this point, more intensive specialization is achieved in the student's field of research through coursework and thesis research.

Admission Requirements

An undergraduate degree in chemical engineering is preferred for master's and doctoral degree applicants. Those with related backgrounds will also be considered, but may be required to complete prerequisite coursework in some areas.

Degree Requirements

For the M.S.

Professional Engineering Option with Concentration

A total of 30 credit hours is required. At least 24 course credit hours must be in chemical engineering including 6 credit hours of Graduate Qualifying Project (GQP), 9 credit hours chosen from the chemical engineering core curriculum, 9 credits of concentration courses, and 6 credits of chemical engineering electives. Students select a concentration in either Bioengineering or Advanced Process Engineering. Bioengineering prepares students for the biotech, pharma and medical device industries, while Advanced Process Engineering focuses on advanced topics in design, control and optimization that are applicable to a wide range of chemical processing. The credit distributions for the different concentrations are shown in Table 1.

The GQP provides a capstone experience in applying chemical engineering skills to real-world problems. GQP's are carried out in cooperation with an industrial partner and with the approval and oversight of a faculty member in Chemical Engineering.

Students must take one required three-credit concentration course plus 6 credits chosen from a list of approved concentration courses. Students in the Bioengineering concentration must take CHE 521: Biochemical Engineering, while students in the Advanced Process Engineering concentration must take CHE 565: Advanced Process Engineering. There is flexibility in other concentration course choices so that students can further tailor their studies to their interests and needs. Courses for each of the concentrations are listed in Table 2. Students can choose additional courses to fulfill their concentration requirement as new courses become available, as long as they receive approval, in advance, from the Professional Engineering Program Director.

Table 1. Professional Engineering Option Credit Distribution

Bioengineering Concentration	Credits
3 Core Courses in CHE	9
2 Chemical Engineering Electives[1]	6
Concentration:	
CHE 521: Biochemical Engineering	3
2 Concentration Courses	6
CHE 590: GQP	6
Total	**30**
Advanced Process Engineering Concentration	**Credits**
3 Core Courses in CHE	9
2 Chemical Engineering Electives[1]	6
Concentration:	
CHE 565: Advanced Process Engineering	3
2 Concentration Courses	6
CHE 590: GQP	6
Total	**30**

[1]Students may choose to take one of these courses in the topic of innovation to gain additional experience in business and for preparation for the GQP, including ETR 500. Entrepreneurship and Innovation. Students should get approval from the Faculty Director for course substitution.

Table 2: Possible Concentration Courses

Bioengineering
BCB 501. Bioinformatics
BCB 502. Biovisualization
BCB 503. Biological and Biomedical Database Mining
BCB 504. Statistical Methods in Genetics and Bioinformatics
BB 505. Fermentation Biology
BB 509. Scale Up of Bioprocessing
BB 560. Methods of Protein Purification and Downstream Processing
BB 562. Cell Cycle Regulation
BME 523. Biomedical Instrumentation
BME/ME 550. Tissue Engineering
CH 538. Medicinal Chemistry
CH 540. Regulation of Gene Expression
BB 565. Virology
BB 575. Advanced Genetics and Cellular Biology
BME 552/ME 552. Tissue Mechanics
CE 562. Biosystems in Environmental Engineering
Advanced Process Engineering
CHE 504. Mathematical Analysis in Chemical Engineering[2]
CHE 506. Kinetics and Catalysis[2]
CHE 507. Chemical Reactor Design[2]
CHE 573. Separation Processes[2]
CHE 531. Fuel Cell Technology
DS 501. Introduction to Data Science
FP 521. Fire Dynamics I
FP 553. Fire Protection Systems
FP 554. Advanced Fire Suppression
FP 555. Detection, Alarm and Smoke Control
FP 573. Industrial Fire Protection
FP 575. Explosion Protection
MFE 510/ ME 542. Control and Monitoring of Manufacturing Processes
MFE 520/ MTE 520/ME 543. Design and Analysis of Manufacturing Processes
MFE/MTE/ME 5420. Fundamentals of Axiomatic Design of Manufacturing Processes
MTE 558. Plastics
MTE 5844. Corrosion and Corrosion Control
ME 516. Heat Transfer
ME/AE 5220. Control of Linear Dynamical Systems
ME/AE 5221. Control of Nonlinear Dynamical Systems
SD 550. System Dynamics Foundation: Managing Complexity
SD 553. Model Analysis and Evaluation Techniques
SYS 501. Concepts of Systems Engineering
SYS 502. Business Practices
SYS 510. Systems Architecture and Design
SYS 512. Requirements Engineering
SYS 520. System Optimization
SYS 521. Model-Based Systems Engineering
SYS 540. Introduction to Systems Thinking

[2]Can be used to satisfy concentration requirements if not taken as part of the core.

Thesis Option

A total of 30 credit hours is required, including 18 credit hours of coursework and at least 12 credit hours of thesis work. The coursework must include 15 credit hours of graduate level chemical engineering courses and 9 of these must be chosen from the core curriculum. A satisfactory oral seminar presentation must be given every year in residence.

Non-Thesis Option

A total of 30 credit hours is required, including a minimum of 24 credit hours in graduate level courses. At least 21 course credit hours must be in chemical engineering and 9 of these must be chosen from the core curriculum. A maximum of 6 credit hours of independent study under the faculty advisor may be part of the program. *Any advanced undergraduate level courses must be approved by the departmental Graduate Committee.*

For the Ph.D.

Upon completion of the comprehensive qualifying examination, candidates must present a research proposal in order to acquaint members of the faculty with the chosen research topic.

Chemical Engineering Laboratories and Centers

Biological Interaction Forces Laboratory

All of the experimental work in this lab is geared at characterizing microbiological and biological systems (bacterial cells, biopolymers, other types of cells, etc.) at the nanoscale. The main piece of equipment used is an atomic force microscope, which can operate in liquids or under ambient conditions. Computers with sophisticated image analysis software are used to quantify phenomena observed in the images. A laminar flow hood is used for working with sterile cultures with ample wet chemistry space to do preparative work.

Microfluidics and Biosensors Laboratory

The research work in this laboratory focuses on integrated microfluidic platform for biomedical applications. Finite element simulation is applied for the study of microfluidics transport and surface reaction kinetics and the design of chip based device. Fabrication of microfluidic biochip by micro/nano manufacturing technologies is of interest in this laboratory. Available equipments include ac impedance analyzer and surface plasmon resonance for the electrical and optical characterization of the biomolecules assembly at the chip surface. Novel micro-and nano-materials and fabrication technology for neuron science and novel nanoassembly for petroleum purification are other two thrusts of interest.

Zeolite Crystallization Laboratory

This laboratory is equipped for hydrothermal syntheses of molecular sieve zeolites over a wide range of temperature, chemical composition and hydrodynamic conditions. The objective is to understand how zeolites nucleate and grow.

Synthesis results are characterized by optical and electron microscopy, X-ray diffraction and particle size analysis.

Heat and Mass Transfer Laboratory

This laboratory is mainly computational. Workstations are dedicated to the application of computational fluid dynamics (CFD) to transport problems in chemical reaction engineering. Current research interests include simulation of flow and heat transfer in packed-bed reactors and membrane reactors. Capabilities also exist in this lab for simulation of gas dynamics in microchannels. Experimental facilities include the measurement of heat and mass transfer coefficients in packed columns.

Catalyst and Reaction Engineering Laboratory (CREL)

A large variety of equipment is available in CREL for catalyst preparation and characterization, and detailed kinetic studies. This includes various reactors such as several packed-bed reactors, a Parr reactor, a slurry reactor, a membrane reactor, a porous-walled tubular reactor and an adiabatic tubular reactor with several thermocouples for monitoring temperature. All necessary analytical instruments are also available, such as several microbalances, volumetric BET apparatus, mercury porosimeter, several gas chromatographs, a Perkin-Elmer GC-MS with Q-Mass 910 mass spectrometer,

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Nicolet Magna-IR 560 FTIR with DRIFT cell for catalyst surface characterization, Rosemount Chemiluminescence NO/NOx Analyzer NGA 2000 and a TEOM Series 1500 PMA Pulse Mass Analyzer for TPD/TGA experiments. Other available equipment in CREL includes hoods, several HPLC liquid feed pumps; several vacuum pumps; temperature, pressure and flow monitors and controllers, furnaces, vacuum oven, diffusion cell, and all necessary glassware and other laboratory supplies for catalyst preparation and testing. In addition, several Macintosh computers and PCs are available within the laboratory. The available equipment is used for the design, synthesis and characterization of novel catalytic materials, and for reactor analysis.

Fuel Cell Laboratory (FCL)

A 5 cm^2 and a 25 cm^2 proton-exchange membrane (PEM) fuel cell test station-complete with flow, pressure, humidity and temperature controllers, and an external electronic load (HP Model No. 6060B) with a power supply (Lambda LFS-46-5)-are available. In addition, a direct methanol fuel cell (DMFC) is available. A hot press, Carver Model C-along with other equipment for casting membranes and for fabricating membrane-electrode assemblies (MEAs) including catalyst preparation equipment-is available.

A cell for studying conductivity at different relative humidities and temperatures is available. Other equipment includes a Solartron SI 1260 AC Impedance Analyzer and a rotating disc electrode. The available equipment allows design and thorough characterization of new fuel cells, including cyclic voltammetry and frequency analysis.

Center for Inorganic Membrane Studies (CIMS)

The goals of the Center for Inorganic Membrane Studies are to develop industry and university collaboration for inorganic membrane research, and to promote and expand the science of inorganic membranes as a technological base for industrial applications through fundamental research. An interdisciplinary approach has been taken by the center to assemble all of the essential skills in synthesis, modeling, material characterization, diffusion measurements and general properties determinations of inorganic membranes. Current projects include dense Pd and Pd/alloy membrane synthesis, and reactive membrane studies, fouling and transport studies, and characterization of membrane stability. Facilities including SEM with EDX , XRD, and several membrane testing units are available.

Fuel Cell Center (FCC)

The Fuel Cell Center is a University/industry alliance comprising industrial members, faculty members, staff, and graduate and undergraduate students. The faculty members of FCC come from the various departments at WPI. The research is performed in the various laboratories of the faculty members. The industrial members represent companies or other organizations with interest in fuel cell technology, including fuel cell companies, automobile manufacturers, utilities, petroleum companies, chemical companies, catalysis companies, etc.

The objectives of the FCC are: (1) to perform research and development of fuel cells, fuel reformers and related components for mobile and stationary applications; (2) to educate graduate and undergraduate students in fuel cell technology; and (3) to facilitate technology transfer between the University and industry. The current projects include development of proton-exchange membrane (PEM) fuel cells, direct methanol fuel cells (DMFCs), molten carbonate fuel cells (MCFCs), microbial fuel cells, fuel cell stacks, membrane reformers, microreformers, reformer catalysis, fuel cell electrocatalysis, composite proton-exchange membranes, inorganic membranes, and transport and reaction modeling.

Course Descriptions

All courses are 3 credits unless otherwise noted.
*Core chemical engineering courses.

CHE 501-502. Seminar
(0 credits)

Reports on current advances in the various branches of chemical engineering or on graduate research in progress. Must be taken during every semester in residence.

CHE 503. Colloquium
(0 credits)

Presentations on scientific advances by recognized experts in various fields of chemical engineering and related disciplines. The course will be graded on a Pass/Fail basis.

CHE 504. Mathematical Analysis in Chemical Engineering*

Methods of mathematical analysis selected from such topics as vector analysis, matrices, complex variables, eigenvalue problems, Fourier analysis, Fourier transforms, Laplace transformation, solution of ordinary and partial differential equations, integral equations, calculus of variation and numerical analysis. Emphasis on application to the solution of chemical engineering problems.

CHE 506. Kinetics and Catalysis*

Theories of reaction kinetics and heterogeneous catalysis for simple and complex reactions. Kinetics and mechanisms of catalyzed and uncatalyzed reactions, and effects of bulk and pore diffusion. Techniques for experimentation, reaction data treatment, and catalyst preparation and characterization.

CHE 507. Chemical Reactor Design*

Includes a review of batch, tubular and stirred tank reactor design. Kinetics review including advanced chemical kinetics and biochemical kinetics, and transport processes in heterogeneous reactions. In-depth reactor analysis includes fixed bed reactors, multiplicity and stability of steady states, reactor dynamics, optimal operation and control, biological reactors, nonideal flow patterns, and fluidized bed and multiphase reactors.

CHE 510. Dynamics of Particulate Systems

Analyzes discrete particles which grow in size or in some other characteristic variable (e.g., age, molecular weight). Reaction engineering and population balance analyses for batch and continuous systems. Steady state and transient system dynamics. Topics may include crystallization, latex synthesis, polymer molecular weight distribution, fermentation/ ecological systems and gas-solid systems.

CHE 521. Biochemical Engineering

Ligand binding and membrane transport processes, growth kinetics of animal cells and micro-organisms, kinetics of interacting multiple populations, biological reactor design and analysis, soluble immobilized enzyme kinetics, optimization and control of fermentation, biopolymer structure and function, properties of biological molecules, biological separation processes, scale-up of bioprocesses; laboratory work may be included when possible.

CHE 531. Fuel Cell Technology

The course provides an overview of the various types of fuel cells followed by a detailed discussion of the proton-exchange membrane (PEM) fuel cell fundamentals: thermodynamics relations including cell equilibrium, standard potentials, and Nernst equation; transport and adsorption in proton-exchange membranes and supported liquid electrolytes; transport in gas-diffusion electrodes; kinetics and catalysis of electrocatalytic reactions including kinetics of elementary reactions, the Butler-Volmer equation, reaction routes and mechanisms; kinetics of overall anode and cathode reactions for hydrogen and direct methanol fuel cells; and overall design and performance characteristics of PEM fuel cells.

CHE 554/CH 554. Molecular Modeling

This course trains students in the area of molecular modeling using a variety of quantum mechanical and force field methods. The approach will be toward practical applications, for researchers who want to answer specific questions about molecular geometry, transition states, reaction paths and photoexcited states. No experience in programming is necessary; however, a backround at the introductory level in quantum mechanics is highly desirable. Methods to be explored include density functional theory, *ab initio* methods, semiempirical molecular orbital theory, and visualization software for the graphical display of molecules.

CHE 561. Advanced Thermodynamics*

Examination of the fundamental concepts of classical thermodynamics and presentation of existence theorems for thermodynamics properties. Inequality of Clausius as a criterion for equilibrium in both chemical and physical systems. Examination of thermodynamic equilibrium for a variety of restraining conditions. Applications to fluid mechanics, process systems and chemical systems. Computation of complex equilibria.

CHE 565. Advanced Process Engineering

Advanced topics in process synthesis, optimization and process control are examined. Optimization topics include objective functions, multivariable optimization, constrained optimization, mixed integer linear programming and applications of optimization to process industries. Control topics include model predictive control, adaptive control, batch process control, and plant-wide control. Recommended background: Undergraduate degree in Chemical Engineering.

CHE 571. Intermediate Transport Phenomena*

Mass, momentum and energy transport; analytic and approximate solutions of the equations of change. Special flow problems such as creeping, potential and laminar boundary-layer flows. Heat and mass transfer in multicomponent systems. Estimation of heat and mass transfer rates. Transport with chemical reaction.

CHE 573. Separation Processes*

Thermodynamics of equilibrium separation processes such as distillation, absorption, adsorption and extraction. Multistaged separations. Principles and processes of some of the less common separations.

CHE 574. Fluid Mechanics*

Advanced treatment of fluid kinematics and dynamics. Stress and strain rate analysis using vectors and tensors as tools. Incompressible and compressible one-dimensional flows in channels, ducts and nozzles. Nonviscous and viscous flow fields. Boundary layers and turbulence. Flow through porous media such as fixed and fluidized beds. Two-phase flows with drops, bubbles and/or boiling. Introduction to non-Newtonian flows.

CHE 580. Special Topics

This course will focus on various topics of current interest related to faculty research experience.

CHE 590. Graduate Qualifying Project in Chemical Engineering

(3 or 6 credits)

These courses provide a capstone experience in applying chemical engineering skills to real-world problems. The Graduate Qualifying Project (GQP) is carried out with an industrial partner or sponsoring agency and with the approval and oversight of a faculty member in chemical engineering. A written report and a presentation to members of the department and industrial partners are required. (Pre-requisites: Completion of core requirements, at least one concentration course and consent of the program director.) Recommended background: Undergraduate degree in Chemical Engineering, completion of the core requirements and at least one concentration course.

Chemistry and Biochemistry

Faculty

A. Gericke, Professor and Department Head; Dr.rer.nat., University of Hamburg; biophysical characterization of lipid-mediated protein function, development of vibrational spectroscopic tools to characterize biological tissue.

J. M. Argüello, Professor; Ph.D., Universidad Nacional de Río Cuarto, Argentina; transmembrane ion transport, metal-ATPases structure-function, bacterial metal homeostasis, role os metals in bacterial pathogenesis.

S. C. Burdette, Associate Professor; Ph.D., Massachusetts Institute of Technology; synthesis of fluorescent sensors for iron, photoactive chelators for delivery of metal ions in cells, applications of azobenzene derivatives with unusual optical properties, polymers to detect metal contaminants in the environment.

R. E. Dempski, Associate Professor; Ph.D., Massachusetts Institute of Technology; molecular mechanism of human zinc transporter, structure-function of light activated channel, optogenetics.

J. P. Dittami, Professor; Ph.D., Rensselaer Polytechnic Institute; medicinal chemistry, organic synthesis, new synthetic methods development.

M. H. Emmert, Associate Professor; Ph.D., Universität Münster, Germany; transition metal catalysts for C-H functionalization and CO2 reduction, sustainable syntheses, and new reagents for direct aminations of C-H bonds.

R. L. Grimm, Assistant Professor; Ph.D., California Institute of Technology; growth and characterization by surface science and by photoelectrochemistry of non-traditional semiconductor materials related to solar energy capture, catalysis, and conversion.

G. A. Kaminski, Associate Professor; Ph.D., Yale University; computational physical and biophysical chemistry, force field development, protein structure and binding, host-guest complex formation, solvation effects.

J. MacDonald, Associate Professor; Ph.D., University of Minnesota; porous crystalline materials composed of organic & coordination compounds, polymorphism of pharmaceutical drugs, crystallization of proteins, surpramolecular assembly on surfaces.

A. Mattson, Associate Professor; Ph.D., Northwestern University; metal-free catalyst design, methodology development, complex molecule synthesis.

C. Perez Olsen, Assistant Professor; Ph.D., University of Washington; characterization of membrane composition by mass spectrometry, quantification of lipid flux with stable isotope tracers, genetic dissection of the regulatory pathways of membrane maintenance.

S. F. Scarlata, Professor, Ph.D., University Illinois Urbana-Champaign; Mechanisms of cell signaling using fluorescence imaging and correlation methods, how mechanical deformation affects calcium fluxes in cells.

Research Interests

The three major areas of research in the department are:

- Biochemistry and Biophysics. Within this area there is active research on a number of topics including heavy metal transport and metal homeostasis of both plants and bacteria, computational biochemistry/biophysics of membrane proteins, enzyme structure and function, and G protein and calcium signaling, membrane protein domains and mechanotransduction.
- Molecular Design and Synthesis. Within this area there is active research on topics encompassing organic synthesis and medicinal chemistry, supramolecular materials, metal ion sensors and chelators, polymorphism in pharmaceutical drugs, spectroscopy and photophysical properties of molecules, catalysis for C-H functionalization, and more.
- Nanotechnology and Materials. This research area encompasses such projects as photonic and nonlinear optical materials, nanoporous and microporous crystals of organic and coordination compounds, molecular interactions at surfaces, and others.

Programs of Study

The Department of Chemistry and Biochemistry offers the M.S. and Ph.D. in both Chemistry and Biochemistry. The major areas of research in the department are biochemistry and biophysics, molecular design and synthesis, and nanotechnology and materials.

Admission Requirements

A B.S. degree with demonstrated proficiency in chemistry or biochemistry is required for entrance to Chemistry and Biochemistry graduate programs.

Degree Requirements

Because graduate education in chemistry and biochemistry is primarily research oriented, there are few formal departmental course requirements in the graduate program. However, it is expected that each graduate student will take graduate level courses in areas of chemistry and biochemistry that are relevant to their field of specialization, as well as seminar courses. Entering students who have deficiencies in specific areas (inorganic, organic, physical, or biochemistry), as revealed by preliminary examinations, will take appropriate courses to correct these deficiencies.

Ph.D. students should select a research advisor no later than at the end of the first semester of residence, and M.S. students should select an advisor no later than at the end of the first term (first seven weeks).

For the M.S.

For the Master of Science in Chemistry or Biochemistry, the student is required to complete a minimum of 30 graduate credit hours beyond the bachelor's degree. Requirements include completing at least 3 credits of CH 560, CH 561 or CH 571. For the remaining 27 credits, the student may choose between a thesis or non-thesis option. In addition to general college requirements, all courses taken for graduate credit must result in a GPA of 3.0 or higher.

Thesis Option

The student must complete a thesis with at least 15 combined credits CH 598 (Directed Research) or CH 599 (M.S. Thesis). Additional credits may consist of any combination of thesis or course electives. Course elective credits must consist of additional CBC or other 4000-, 500- or 600-level engineering, science, management or mathematics electives. All course selections must be approved by the student's research advisor and the CBC Graduate Committee prior to registering. Each student should select a research advisor by the end of the first semester of study. M.S. candidates must submit and defend a thesis based on research conducted under the direction of a CBC faculty member. The thesis committee consists of at least three members, two of whom must belong to the CBC Department faculty.

Non Thesis Option

Graduate credits must consist of 4000-, 500- or 600-level courses. Credits should be distributed as follows:

- At least 15 credits in CBC courses.
- A maximum of 10 credits in electives in areas of engineering, science, management or mathematics.
- Students also may use up to 9 credits of CH 598 (Directed Research) toward credit hour requirements.

Biochemistry students will be advised to take graduate courses in Membrane Biophysics (CH 541), Molecular Modeling (CH 554), Medicinal Chemistry (CH 538), and Spectroscopy (CH 516) in addition to advanced Biochemistry courses. Among electives in other areas, these might include courses on applied Biochemistry/Biological processes (BB 560/BB 505/BB 509) and Bioinformatics (BCB 501/BCB 502/BCB 503).

Chemistry students will be advised to take graduate courses in Theory and Applications of NMR Spectroscopy (CH 536), Molecular Modeling (CH 554), Medicinal Chemistry (CH 538), and Spectroscopy (CH 516) in addition to advanced Chemistry courses. Among electives in other areas, these might include courses on Chemical Engineering (CHE 506/CHE 521/CHE 561) applied Biochemistry/Biological processes (BB 560/BB 505/BB 509).

No Combined B.S./M.S. Degree

CBC does not offer a combined B.S./M.S. degree.

For the Ph.D.

Each student should select a research advisor by the end of the first semester of residence. At the end of the first semester of the second year of residence, the student must submit a written and an oral progress report in the dissertation committee of at least four faculty members, including the Research Advisor, at least two more members of the Department, and at least one person from outside the Department. The committee will consider the student's progress and will recommend to the department whether the student should be allowed to continue toward a Ph.D.

Qualifying Examination

Before formal admission to the doctoral candidacy, Ph.D. students must take the qualifying examination in their field of specialization. The examination should take place before the end of the second year of residence.

Dissertation

To fulfill the final Ph.D. degree requirement the candidate must submit and defend a satisfactory dissertation to the dissertation committee.

Chemistry and Biochemistry Research Laboratories

The Chemistry and Biochemistry Research Laboratories are located in Goddard Hall and at Gateway Park. Department facilities and instrumentation in individual research laboratories include 500 and 400 MHz FT-NMR, GC-MS, GC, HPLC, capillary electrophoresis, DSC (differential scanning calorimeter), TGA (thermogravometric analysis), polarizing optical stereomicroscope, FT-IR, UV-VIS absorption, fluorescence and phosphorescence spectroscopy; powder and single crystal x-ray diffractometers, cyclic voltammetry, impedence spectroscopy, ellipsometer, quartz crystal microbalance, grazing incidence IR, atomic force microscope (AFM), and other surface-related facilities. Additional equipment in the biochemistry area include: centrifugues, ultra-centrifugues, PCR, phospho imager, scintillation counter, FPLC, bacteria and eukaryotic cell culture and plant growth facilities. The department is exceptionally well set up with computer facilities and is also linked to the University's network.

Course Descriptions

All courses are 3 credits unless otherwise noted.

CH 516. Chemical Spectroscopy

The emphasis is on using a variety of spectroscopic data to arrive at molecular structures, particularly of organic molecules. Major emphasis is on H- and C-NMR, IR and MS. There is relatively little emphasis on theory or on sampling handling techniques.

CH 536. Theory and Applications of NMR Spectroscopy

This course emphasizes the fundamental aspects of 1D and 2D nuclear magnetic resonance spectroscopy (NMR). The theory of pulsed Fourier transform NMR is presented through the use of vector diagrams. A conceptual nonmathematical approach is employed in discussion of NMR theory. The course is geared toward an audience which seeks an understanding of NMR theory and an appreciation of the practical applications of NMR in chemical analysis. Students are exposed to hands-on NMR operation. Detailed instructions are provided and each student is expected to carry out his or her own NMR experiments on a Bruker AVANCE 400 MHz NMR spectrometer.

CH 538. Medicinal Chemistry

This course will focus on the medicinal chemistry aspects of drug discovery from an industrial pharmaceutical research and development perspective. Topics will include chemotherapeutic agents (such as antibacterial, antiviral and antitumor agents) and pharmacodynamic agents (such as antihypertensive, antiallergic, antiulcer and CNS agents). (Prerequisite: A good foundation in organic chemistry, e.g., CH 2310 Organic Chemistry I and CH 2320 Organic Chemistry II.)

CH 540. Regulation of Gene Expression

(2 credits)

This course covers the biochemical mechanisms involved in regulation of gene expression: modifications of DNA structures that influence transcription rates, transcriptional regulation, post-transcriptional processing of RNA including splicing and editing, nuclear/cytoplasmic transport, regulation of translation, and factors that control the half-lives of both mRNA and protein. During the course, common experimental methods are explored, including a discussion of the information available from each method.

CH 541. Membrane Biophysics
(2 credits)
This course will focus on different areas of biophysics with special emphasis on membrane phenomena. The biomedical-biological importance of biophysical phenomena will be stressed. The course will begin with an introduction to the molecular forces relevant in biological media and subsequently develop the following topics: membrane structure and function; channels, carriers and pumps; nerve excitation and related topics; and molecular biophysics of motility. Topics will be developed assuming a good understanding of protein and lipid chemistry, enzyme kinetics, cell biology, and electricity.

CH 554/CHE 554. Molecular Modeling
This course trains students in the area of molecular modeling using a variety of quantum mechanical and force field methods. The approach will be toward practical applications, for researchers who want to answer specific questions about molecular geometry, transition states, reaction paths and photoexcited states. No experience in programming is necessary; however, a backround at the introductory level in quantum mechanics is highly desirable. Methods to be explored include density functional theory, *ab initio* methods, semiempirical molecular orbital theory, and visualization software for the graphical display of molecules.

CH 555. Advanced Topics
(1 to 3 credits as arranged)
A course of advanced study in selected areas whose content and format varies to suit the interest and needs of faculty and students. This course may be repeated for different topics covered.

CH 560. Current Topics in Biochemistry
(1 credit per semester)
In this seminar course, a different topic is selected each semester. Current articles are read and analyzed.

CH 561. Functional Genomics
(1 credit per semester)
In this seminar course, students will present and critically analyze selected, recent publications in functional genomics. The course will conclude with a written project, either a mini-grant proposal or an analysis of publicly available data in a research manuscript format. The course will be offered in alternate years in lieu of CH 560, may be repeated as many times as offered, and satisfies the department's requirement for a graduate seminar in biochemistry. *This course is offered by special arrangement only, based on expressed student interest.*

CH 571. Seminar
(1 credit per semester)
Reports on current advances in the various branches of chemistry.

CH 598. Directed Research

CH 599. M.S. Thesis

CH 699. Ph.D. Dissertation

The following graduate/undergraduate chemistry courses are also available for graduate credit.

CH 4110. Biochemistry I
The principles of protean structure are presented. Mechanisms of enzymatic catalysis, including those requiring coenzymes, are outlined in detail. The structures and biochemical properties of carbohydrates are reviewed. Bioenergetics, the role of ATP, and its production through glycolysis and the TCA cycle are fully considered.

CH 4120. Biochemistry II
Oriented around biological membranes, this term begins with a discussion of electron transport and the aerobic production of ATP, followed by a study of photosynthesis. The study of the biosynthesis of lipids and steroids leads to a discussion of the structure and function of biological membranes. Finally, the membrane processes in neurotransmission are discussed. (Recommended background: CH 4110.)

CH 4130. Biochemistry III
This course presents a thorough analysis of the biosynthesis of DNA (replication), RNA (transcription) and proteins (translation), and of their biochemical precursors. Proteins and RNAs have distinct lifetimes within the living cell; thus the destruction of these molecules is an important biochemical process that is also discussed. In addition to mechanistic studies, regulation of these processes is covered.

CH 4330. Organic Synthesis
A discussion of selected modern synthetic methods including additions, condensations and cyclizations. Emphasis is placed on the logic and strategy of organic synthesis. (Recommended background: CH 2310, CH 2320 and CH 2330, or the equivalent.) This course will be offered in 2012-13 and in alternate years thereafter.

CH 4420. Inorganic Chemistry II
Complexes of the transition metals are discussed. Covered are the electronic structures of transition metal atoms and ions, and the topological and electronic structures of their complexes. Symmetry concepts are developed early in the course and used throughout to simplify treatments of electronic structure. The molecular orbital approach to bonding is emphasized. The pivotal area of organotransition metal chemistry is introduced, with focus on complexes of carbon monoxide, metal-metal interactions in clusters, and catlysis by metal complexes. (Recommended background: CH 2310 and CH 2320, or equivalent.) This course will be offered in 2011-12 and in alternate years thereafter.

CH 4520. Chemical Statistical Mechanics
This course deals with how the electronic, translational, rotational and vibrational energy levels of individual molecules, or of macromolecular systems are statistically related to the energy, entropy and free energy of macroscopic systems, taking into account the quantum mechanical properties of the component particles. Ensembles, partition functions, and Boltzmann, Fermi/Dirac and Bose-Einstein statistics are used. A wealth of physical chemical phenomena, including material related to solids, liquids, gases, spectroscopy and chemical reactions are made understandable by the concepts learned in this course. This course will be offered in 2011-12 and in alternate years thereafter.

Civil and Environmental Engineering www.wpi.edu/+cee

Faculty

T. El-Korchi, Professor and Department Head; Ph.D., University of New Hampshire; glass fiber reinforced cement composites, tensile testing techniques, materials durability.

L. D. Albano, Associate Professor; Ph.D., Massachusetts Institute of Technology; performance-based design of buildings, design and behavior of building structures in fire conditions, integration of design and construction.

J. Bergendahl, Associate Professor; Ph.D., University of Connecticut; industrial and domestic wastewater treatment, particulate processes in the environment, chemical oxidation of contaminants.

R. B. Mallick, Professor and White Chair; Ph.D., Auburn University; nondestructive testing, highway design, pavement material characterization.

P. P. Mathisen, Associate Professor; Ph.D., Massachusetts Institute of Technology; water resources and environmental fluid dynamics, contaminant fate and transport in groundwater and surface water, exchanges across the sediment-water interface.

J. Plummer, Associate Professor; Ph.D., University of Massachusetts Amherst; surface water quality, drinking water treatment, public health.

N. Rahbar, Associate Professor; Ph.D., Princeton University; atomistic simulations, bioinspired design of materials, contact mechanics and adhesion, computational material science.

A. Sakulich, Assistant Professor; Ph.D., Drexel University; sustainability of infrastructure materials, alternative binders, and advanced civil engineering systems.

G. F. Salazar, Associate Professor; Ph.D., Massachusetts Institute of Technology; integration of design and construction, models and information technology, cooperative agreements.

M. Tao, Associate Professor; Ph.D., Case Western Reserve University; soil mechanics, geotechnical-pavement engineering, geo-material characterization and modeling.

S. Van Dessel, Associate Professor; Ph.D., University of Florida, Gainesville; architectural engineering, building materials.

Programs of Study

The Department of Civil and Environmental Engineering (CEE) offers graduate programs leading to the degrees of master of science, master of engineering and doctor of philosophy. The department also offers graduate and advanced certificate programs. Full- and part-time programs of study are available.

Master of Science and Doctor of Philosophy

The graduate programs in civil engineering and environmental engineering are arranged to meet the interests and objectives of the individual student. Through consultation with an advisor and appropriate selection from the courses listed in this catalog, independent graduate study and concentrated effort in a research or project activity, a well-planned program may be achieved. Students may take acceptable courses in other departments or those approved for graduate credit. The complete program must be approved by the student's advisor and the Graduate Program Coordinator.

The faculty have a broad range of teaching and research interests. Through courses, projects and research, students gain excellent preparation for rewarding careers in many sectors of engineering including consulting, industry, government and education.

Graduate programs may be developed in the following areas:

Structural Engineering

Courses from the structural offerings, combined with appropriate mathematics, mechanics and other courses, provide opportunities to pursue programs ranging from theoretical mechanics and analysis to structural design and materials research. There are ample opportunities for research and project work in mechanics, structures and construction utilizing campus facilities and in cooperation with area consulting and contracting firms. The integration of design and construction into a cohesive master builder plan of studies is available. (See page 69).

Some current and recent structural engineering research topics at WPI include: structural vibration control; structural health monitoring; system identification; design and analysis of smart structures; high impact response analysis; control and monitoring; three-dimensional dynamic response of tall buildings to stochastic winds; the inelastic dynamic response of tall buildings to earthquakes; evaluation of structural performance during fire conditions; structural design agents for building design; finite element methods for nonlinear analysis; finite element analysis of shell structures for dynamic and instability analysis; and box girder bridges.

Environmental Engineering

The environmental engineering program is designed to meet the needs of engineers and scientists in the environmental field. Coursework provides a strong foundation in both the theoretical and practical aspects of the environmental engineering discipline, while project and research activities allow for in-depth investigation of current and emerging topics. Courses are offered in the broad areas of water quality and waste treatment. Topics covered in classes include: hydraulics and hydrology; physical, chemical and biological treatment systems for water, wastewater, hazardous waste and industrial waste; modeling of contaminant transport and transformations; water quality and water resources.

Current research interests in the environmental engineering program span a wide range of areas. These areas include microbial contamination of source waters, colloid and surface chemistry, physiochemical treatment processes, disinfection, pollution prevention for industries, treatment of hazardous and industrial wastes, hydraulic and environmental fluid dynamics and coastal processes, contaminant fate and transport in groundwater and surface

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water, exchanges between surface and subsurface waters, and storm water quality control. Research facilities include the Environmental Laboratory and several computing laboratories. Additional opportunities are provided through collaborative research projects with nearby Alden Research Laboratory, an independent hydraulics research laboratory with large-scale experimental facilities.

Geotechnical Engineering

Course offerings in soil mechanics, geotechnical and geoenvironmental engineering may be combined with structural engineering and engineering mechanics courses, as well as other appropriate university offerings.

Engineering and Construction

Designed to assist the development of professionals knowledgeable in the design/construction engineering processes, labor and legal relations, and the organization and use of capital. The program has been developed for those students interested in the development and construction of large-scale facilities. The program includes four required courses: CE 580, CE 584, CE 587 and FIN 500. (FIN 500 can be substituted by an equivalent 3-credit-hour course approved by the department.) It must also include any two of the following courses: CE 581, CE 582, CE 583 and CE 586. The remaining courses include a balanced choice from other civil engineering and management courses as approved by the advisor. It is possible to integrate a program in design and construction to develop a cohesive master builder plan of studies. Active areas of research include integration of design and construction, models and information technology, cooperative agreements, and international construction.

Transportation Engineering

The transportation engineering program is to provide a center for education and research for the engineers who will design, build and conduct cutting-edge research on transportation infrastructure.

The transportation engineering program is a multidisciplinary interdepartmental program designed to prepare students for careers designing, maintaining and managing transportation infrastructure systems. Students gain proficiency in transportation engineering in two complementary ways: projects and coursework. Projects focus on developing improved practical methods, procedures and techniques. Coursework is focused on practical aspects of infrastructure technology needed by practicing engineers.

Research in the transportation engineering program is sponsored by a variety of private and governmental organizations including the U. S. Federal Highway Administration, the National Cooperative Highway Research Program, the Massachusetts Highway Department, The Maine Department of Transportation, the New England Transportation Consortium, the National Science Foundation and others. Some of the more active research areas being pursued in the transportation engineering program include micro/nano characterization and micro/nano mechanics of construction materials, synthesizing 'greener' cementitious materials (geopolymers) from industrial wastes, understanding fundamental behavior of granular materials, energy harvesting from pavements, reduction of pavement temperatures and urban heat island effects, high reclaimed asphalt pavement (RAP) recycling, use of geosynthetics, phase changing materials, Superpave technology, pavement smoothness and ride quality measurement, recycled asphalt materials, and implementation of innovation in transportation management and other transportation-related topics.

Interdisciplinary M.S. Program in Construction Project Management

The interdisciplinary M.S. program in construction project management combines offerings from several disciplines including civil engineering, management science, business and economics. Requirements for the degree are similar to the master of science in engineering and construction management program.

Master of Engineering

The master of engineering degree is a professional practice-oriented degree. The degree is available both for WPI undergraduate students who wish to remain at the university for an additional year to obtain both a bachelor of science and a master of engineering, as well as for students possessing a B.S. degree who wish to enroll in graduate school to seek this degree. At present, the M.E. program is offered in the following two areas of concentration:

Master Builder

The master builder program is designed for engineering and construction professionals who wish to better understand the industry's complex decision-making environment and to accelerate their career paths as effective project team leaders.

This is a practice-oriented program that builds upon a project-based curriculum and uses a multidisciplinary approach to problem solving for the integration of planning, design, construction and facility management. It emphasizes hands-on experience with information technology and teamwork.

Environmental

The environmental master of engineering program concentrates on the collection, storage, treatment and distribution of industrial and municipal water resources and on pollution prevention and the treatment and disposal of industrial and municipal wastes.

Admission Requirements

For the M.S.

An ABET accredited B.S. degree in civil engineering (or another acceptable engineering field) is required for admission to the M.S. program in civil engineering. Applicants are expected to have the necessary academic preparation and aptitude to succeed in a challenging graduate program. Students who do not have an ABET accredited B.S. degree may wish to enroll in the inderdisciplinary M.S. program.

For the environmental engineering program, a B.S. degree in civil, chemical or mechanical engineering is normally required. However, students with a B.S. in other engineering disciplines as well as physical and life sciences are eligible, provided they have met the undergraduate math and science requirements of the civil and environmental engineering program. A course in the area of fluid mechanics is also required. As for the civil engineering degree program, applicants are expected to

have the necessary background preparation and aptitude to succeed in a challenging graduate program. All graduates of this option will receive a master of science in environmental engineering.

For the interdisciplinary M.S. program in construction project management, students with degrees in areas such as architecture, management engineering and civil engineering technology are normally accepted to this program. Management engineering students may be required to complete up to one year of undergraduate civil engineering courses before working on the M.S.

For the M.E.

A B.S. degree in civil engineering (or another acceptable engineering field) is required for admission to the M.E. program in civil engineering.

For the Ph.D.

Ph.D. applicants must have earned a bachelor's or master's degree. Applicants will be evaluated based on their academic background, professional experience, and other supporting application material. As the dissertation is a significant part of the Ph.D., applicants are encouraged, prior to submitting an application, to make contact with CEE faculty performing research in the area the applicant wishes to pursue.

Degree Requirements

For the M.S.

The completion of 30 semester hours of credit, of which 6 credits must be research or project work, is required. A non-thesis alternative consisting of 33 semester hours is also available. In addition to civil and environmental engineering courses, students also may take courses relevant to their major area from other departments. Students who do not have the appropriate undergraduate background for the graduate courses in their program may be required to supplement the 30 semester hours with additional undergraduate studies.

For the M.E.

The master of engineering degree requires the completion of an integrated program of study that is formulated with a CEE faculty advisor at the start of the course of study. The program and subsequent modifications thereof must be submitted to and approved by the CEE department head or the Graduate Program Coordinator, when they are developed or changed. The program requires the completion of 30 semester hours of credit. The following activities must be fulfilled through completion of the courses noted or by appropriate documentation by the department head or graduate program coordinator: experience with complex project management (CE 593 Advanced Project), competence in integration of computer applications and information technology (CE 587 Building Information Modeling), and knowledge in the area of professional business practices and ethics (CE 501 Professional Practice). The program shall also include coursework in at least two subfields of civil and environmental engineering that are related to the M.E. area of specialization.

The primary subfield will provide the student with competence required for the analysis of problems encountered in practice and the design of engineering processes, systems and facilities. Subfields are currently available in structural engineering, engineering and construction management, highway and transportation engineering, geotechnical engineering, materials engineering, geohydrology, water quality management, water resources, waste management, and impact engineering. The sub-field requirements are satisfied by completing two thematically related graduate courses that have been agreed upon by both the student and the advisor as appropriate to the program of study. In addition to the subfields noted above, other appropriate areas may be identified as long as it is clear that the courses represent advanced work and complement the program. Coursework and other academic experiences to fulfill this requirement will be defined in the integrated Plan of Study at the start of the program.

Transfer between M.S. and M.E. Program

A student may transfer from the M.E. program to the M.S. program at any time. A student may transfer from the M.S. program to the M.E. program only after an integrated program of study has been agreed upon by the student and the advisor in the area of concentration and approved by the CEE department head or the Graduate Program Coordinator.

For the Ph.D.

Doctoral students must satisfactorily complete a qualifying examination administered within the first 18 credits of admission into the Ph.D. program. The purpose of the qualifying examination is to assess the student's ability to succeed at the Ph.D. level and also to identify strengths and weaknesses in order to plan an appropriate sequence of courses. The exam is administered by a four member committee consisting of the major advisor and three other members selected by the major advisor.

In addition to the university requirements for the Ph.D. degree, the CEE department requires students to establish a minor and to pass a comprehensive examination. Students must establish a minor outside their major area. This may be accomplished with three courses in the approved minor area. One member of the student's dissertation committee should represent the minor area. The student's dissertation committee has the authority to make decisions on academic matters associated with the Ph.D. program. To become a candidate for the doctorate, the student must pass a comprehensive examination administered by the student's dissertation committee. The candidate, on completion and submission of the dissertation, must defend it to the satisfaction of the dissertation committee.

Civil and Environmental Engineering Laboratories

The department has five civil and environmental engineering laboratories (Environmental Lab, Geotechnical Lab, Materials/Structural Lab, Structural Impact Lab and Pavement Engineering Lab), plus three computer laboratories located within Kaven Hall. The CEE laboratories are used by all civil and environmental engineering students and faculty. The computer laboratories are open to all WPI students and faculty. Uses for all laboratories include formal classes, student projects, research projects and unsupervised student activities.

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Computer Laboratories

The CEE Department has a number of computer laboratories that are located in Kaven Hall and connected to WPI's network. The computer laboratories contain up-to-date computers, network connections, and presentation systems. They are used for courses, group project work and research.

Fuller Environmental Laboratory

The Fuller Laboratory is designed for state-of-the-art environmental analyses, including water and wastewater testing and treatability studies. Major equipment includes an inductively coupled plasma mass spectrometer, total organic carbon analyzer, UV-Vis spectrophotometer, particle counter, an ion chromatograph, and two gas chromatographs. Along with ancillary equipment (such as a centrifuge, autoclave, incubators, balances, pH meters and water purification system), the laboratory is equipped for a broad range of physical, chemical and biological testing. The laboratory is shared by graduate research projects, graduate and undergraduate courses (e.g. CE 4060 Environmental Engineering Laboratory) and undergraduate projects.

Geo/Water Resources Laboratory

The geo-water resources laboratory is a flexible teaching and research space that provides support for research, undergraduate and graduate projects, and courses in the areas of geotechnical engineering and water resources. The laboratory provides bench-top laboratory space for completing soil and water quality analyses, a flexible area for working with larger lab configurations that cannot be placed on the bench-top, space for preparing equipment and supplies for field investigations, and a secure area for testing, developing, and storing both field and laboratory equipment. Laboratory equipment includes fully automated stress-path-control triaxial testing system, flexible wall permeameter, and other devices for determining basic soil properties, and an aquarium and variety of tanks for demonstrating and testing equipment in water. Field equipment includes flowmeters, pumps for groundwater sampling, multiparameter water quality monitoring, and a variety of equipment for hydrologic monitoring and water quality testing.

Materials/Structural Laboratory

The Materials/Structural Laboratory is set up for materials and structures testing. The laboratory is utilized for undergraduate teaching and projects, and graduate research. The laboratory is equipped for research activities including construction materials processing and testing. Materials tested in this lab include portland cement, concrete, asphalt, and fiber composites. The laboratory has several large-load mechanical testing machines.

Pavement Research Laboratory

The pavement research laboratory provides support for graduate research and courses. The state of the art array of equipment includes compactor, moisture susceptibility testing equipment, loaded wheel tester and extraction and recovery equipment. The laboratory contains some of the most advanced testing equipment – most notable of these are the material testing system, the Model Mobile Load Simulator, and an array of Non Destructive Testing equipment consisting of the Portable Seismic Property Analyzer, Falling Weight Deflectometer and Ground Penetrating Radar. A major focus of the pavement engineering program is on the integration of undergraduate and graduate curriculum with research projects funded by the Maine Department of Transportation, Federal Highway Administration, New England Transportation Consortium and National Science Foundation.

Structural Mechanics Impact Laboratory

The Structural Mechanics Impact Laboratory is a teaching and research laboratory. The impact laboratory is used to explore the behavior of materials and components in collisions.

The Structural Mechanics Impact Laboratory consists of the following major pieces of equipment:

- An Instron Dynatup Model 8250 Instrumented Impact Test System,
- A high-speed video camera system,
- A data acquisition system,
- A large-mass drop tower,
- A space control desk, and
- National Instrument Lab View.

Course Descriptions

All courses are 3 credits unless otherwise noted.

CE 501. Professional Practice

Professional practices in engineering. Legal issues of business organizations, contracts and liability; business practice of staffing, fee structures, accounts receivable, negotiation and dispute resolution, and loss prevention; marketing and proposal development; project management involving organizing and staffing, budgeting, scheduling, performance and monitoring, and presentation of deliverables; professionalism, ethics and responsibilities.

CE 510. Structural Mechanics

Analysis of structural components: uniform and nonuniform torsion of structural shapes, analysis of determinate and indeterminate beams (including elastic foundation conditions) by classical methods, finite difference equations, numerical integrations, series approximation, elastic stability of beams and frames, lateral stability of beams, beams-columns, analysis of frames including the effect of axial compression.

CE 511. Structural Dynamics

Analysis and design of beams and frames under dynamic loads; dynamics of continuous beams, multistory building frames, floor systems and bridges; dynamic analysis and design of structures subjected to wind and earthquake loads; approximate methods of analysis and practical design applications.

CE 514/ME 5383. Continuum Mechanics

(2 credits)

This course covers the fundamentals of continuum mechanics at an introductory graduate level. Topics covered include: 1) Introduction: essential mathematics - scalars, vectors, tensors, and indicial notation; 2) Basics: three-dimensional states of stress, finite and infinitesimal measures strain, and principal axes; 3) Conservations laws: mass, linear momentum, angular momentum and energy; 4) Constitutive equations: ideal materials, Newtonian fluids, isotropy and anisotropy, elasticity and thermoelasticity, plasticity, and viscoelasticity; 5) Applications to classical problems and emerging topics in solid and fluid mechanics. Recommended background: undergraduate knowledge of strength of materials, fluid mechanics, and linear algebra.

CE 519. Advanced Structural Analysis

Energy methods in structural analysis, concepts of force method and displacement methods, methods of relaxation and numerical techniques for the solution of problems in buildings, and long-span structures and aircraft structural systems. Effects of secondary stress in structures. Course may be offered by special arrangement. (Prerequisites: Structural mechanics and undergraduate courses in structural analysis, differential equations.)

CE 523. Advanced Matrix Structural Analysis

Matrix methods of structural analysis, displacement and flexibility methods; substructuring, tall buildings, energy methods, finite elements, including plane stress and strain elements, approximate methods, solution of linear systems.

CE 524. Finite Element Method and Applications

This course serves as an introduction to the basic theory of the finite element method. Topics covered include matrix structural analysis variation form of differential equations, Ritz and weighted residual approximations, and development of the discretized domain solution. Techniques are developed in detail for the one- and two-dimensional equilibrium problem. Examples focus on elasticity and heat flow with reference to broader applications. Students are supplied microcomputer programs and gain experience in solving real problems. Prerequisites: Elementary differential equations, solid mechanics and heat flow. Note: Students cannot receive credit for both this course and CE/ME 5303 Applied Finite Element Methods.

CE/ME 5303. Applied Finite Element Methods in Engineering

(2 credits)

This course is devoted to the numerical solution of partial differential equations encountered in engineering sciences. Finite element methods are introduced and developed in a logical progression of complexity. Topics covered include matrix structural analysis variation form of differential equations, Ritz and weighted residual approximations, and development of the discretized domain solution. Techniques are developed in detail for the one- and two-dimensional equilibrium and transient problems. These numerical strategies are used to solve actual problems in heat flow, diffusion, wave propagation, vibrations, fluid mechanics, hydrology and solid mechanics. Weekly computer exercises are required to illustrate the concepts discussed in class. Students cannot receive credit for this course if they have taken the Special Topics (ME 593E) version of the same course or ME 533 or CE 524.

CE 531. Advanced Design of Steel Structures

Advanced design of steel members and connections; ultimate strength design in structural steel; codes and specifications; loads and working stresses; economic proportions; and buckling of slender elements and built-up sections, torsion, lateral-torsional buckling, beam-columns, design for lateral forces, and connections for building frames.

CE 532. Advanced Design of Reinforced Concrete Structures

Advanced design of reinforced concrete members and structural systems; effect of continuity; codes and specifications; ultimate strength theory of design; economic proportions and constructibility considerations; and deep beams, torsion, beam-columns, two-way slabs, design for lateral forces, and beam-to-column joints.

CE 534. Structural Design for Fire Conditions

The development of structural analysis and design methods for steel and reinforced concrete members subjected to elevated temperatures caused by building fires. Beams, columns and rigid frames will be covered. The course is based on research conducted during the past three decades in Europe, Canada and the United States. Course may be offered by special arrangement. (Prerequisites: Knowledge of statically indeterminate structural analysis, structural steel design and reinforced concrete design.)

CE 535. Integration of Design and Construction

As an interactive case study of the project development process, student groups design a facility and prepare a construction plan, including cost and schedule, to build the project. The students present their design-build proposal to participating industrial clients. Emphasis is on developing skills to generate, evaluate and select design alternatives that satisfy the needs of the owner and the constraints imposed by codes and regulations, as well as by the availability of construction resources. Emphasis is also in developing team-building skills and efficient communication. Computer-based methods for design, construction cost estimating and scheduling, and personal communications are extensively used. The interactive case study is specifically chosen to balance the content between design, construction engineering and management. Students taking this course are expected to have a background in at least two of these disciplines.

CE 536. Construction Failures: Analysis and Lessons

This course develops an understanding of the integration process of technical, human, capital, social and institutional aspects that drive the life cycle of a construction project. The study of failures provides an excellent vehicle to find ways for the improvement of planning, design and construction of facilities. Student groups are required to complete a term project on the investigation of a failure and present their findings and recommendations. This investigation includes not only the technical analysis of the failure but also requires a comprehensive analysis of the organizational, contractual and regulatory aspects of the process that lead to the failure. The course uses case studies to illustrate different types of failure in the planning, design, construction and operation of constructed facilities. Students taking this course are expected to have a sound academic or practical background in the disciplines mentioned above.

CE 538. Pavement Analysis and Design for Highways and Airports

This course is designed for civil engineers and provides a detailed survey of analysis and design concepts for flexible and rigid pavements for highways and airports. The material covers elastic and inelastic theories of stress pavement components and currently used design methods, i.e., Corps of Engineers, AASHTO, etc. The use of finite element methods for pavement stress and deformation analysis are presented. A review of pavement rehabilitation methods and processes is presented. (Prerequisites: differential equations, construction materials, soil mechanics, computer literacy.)

CE 542. Geohydrology

This course addresses engineering problems associated with the migration and use of subsurface water. An emphasis is placed on the geology of water-bearing formations including the study of pertinent physical and chemical characteristics of soil and rock aquifers. Topics include principles of groundwater movement, geology of groundwater occurrence, regional groundwater flow, subsurface characterization, water well technologies, groundwater chemistry and unsaturated flow.

CE 560. Advanced Principles of Water Treatment

Theory and practice of drinking water treatment. Water quality and regulations; physical and chemical unit processes including disinfection, coagulation, clarification, filtration, membranes, air stripping, adsorption, softening, corrosion control, and other advanced processes.

CE 561. Advanced Principles of Wastewater Treatment

Theory and practice of wastewater treatment. Natural purification of streams; screening; sedimentation; flotation, thickening; aerobic treatment methods; theory of aeration; anaerobic digestion; disposal methods of sludge including vacuum filtration, centrifugation and drying beds; wet oxidation; removal of phosphate and nitrogen compounds; and tertiary treatment methods.

CE 562. Biosystems in Environmental Engineering

Application of microbial and biochemical understanding to river and lake pollution; natural purification processes; biological conversion of important elements such as C, N, S, O and P; biological aspects of wastewater treatment; disease-producing organisms with emphasis on water-borne diseases; and quantitative methods used in indicator organism counts and disinfection.

CE 5621. Open Channel Hydraulics

This course begins with fundamentals of free surface flow, and includes engineering and environmental applications. Development of basic principles, including specific energy, momentum and critical flow. Rapidly varied, uniform and gradually varied steady flow phenomena and analysis. Density-stratified flow. Similitude considerations for hydraulic models. Optional topics: dispersion and heat transfer to atmosphere. Course may be offered by special arrangement.

CE 563. Industrial Waste Treatment
Legislation; the magnitude of industrial wastes; effects on streams, sewers and treatment units; physical, chemical and biological characteristics; pretreatment methods; physical treatment methods; chemical treatment methods; biological treatment methods; and wastes from specific industries. Lab includes characterization and treatment of typical industrial wastes.

CE 565. Surface Water Quality Modeling
This course provides a quantitative analysis of the fate and transport of contaminants in surface water systems. Water quality models are developed using a mass balance approach to describe the transport, dispersal, and chemical/biological reactions of substances introduced into river and lake systems. Topics covered include water quality standards, model formulation and application, waste load allocation, and water quality parameters such as biochemical oxygen demand, dissolved oxygen, nutrients, and toxic chemicals.

CE 566. Groundwater Flow and Pollution
This course provides a review of the basic principles governing ground water flow and solute transport, and examines the models available for prediction and analysis including computer models. Topics covered include mechanics of flow in porous media; development of the equations of motion and of conservation of solute mass; analytical solutions; and computer-based numerical approaches and application to seepage, well analysis, artificial recharge, groundwater pollution, salinity intrusion and regional groundwater analyses.

CE 567. Hazardous Waste: Containment, Treatment and Prevention
This course provides a survey of the areas associated with hazardous waste management. The course materials deal with identification of hazardous waste legislation, containment, storage, transport, treatment and other hazardous wastes management issues. Topics include hazardous movement and containment strategies, barrier design considerations, hazardous waste risk assessment, spill response and clean-up technologies, centralized treatment facilities, on-site treatment, in situ treatment, and industrial management and control measures. Design of selected containment and treatment systems, and a number of industrial case studies are also covered. This course is offered to students with varying backgrounds. Students interested in taking this course must identify a specific problem that deals with either regulation, containment of hazardous waste, treatment of hazardous waste or industrial source reduction of hazardous waste. This problem becomes the focal point for in-depth study. The arrangement of topics between the students and the instructor must be established by the third week. A knowledge of basic chemistry is assumed.

CE 570. Contaminant Fate and Transport
This course introduces the concepts of contaminant fate and transport processes in the environment, with consideration to exchanges across phase boundaries and the effects of reactions on environmental transport. Topics include equilibrium conditions at environmental interfaces, partitioning and distribution of contaminants in the environment, transport and exchange processes in surface water; dispersion, sorption, and the movement of non-aqueous phase liquids in ground-water, and local, urban and regional scale transport processes in the atmosphere.

CE 571. Water Chemistry
This course covers the topics of chemical equilibrium, acid/base chemistry, the carbonate system, solubility of metals, complexation and oxidation-reduction reactions. These principles will be applied to understanding of the chemistry of surface waters and groundwaters, and to understanding the behavior of chemical processes used in water and wastewater treatment.

CE 572. Physical and Chemical Treatment Processes
This course presents the physical and chemical principles for the treatment of dissolved and particulate contaminants in water and wastewater. These concepts will provide an understanding of the design of commonly used unit operations in treatment systems. Applications will be discussed as well. Topics covered include water characteristics, reactor dynamics, filtration, coagulation/flocculation, sedimentation, adsorption, gas stripping, disinfection, and chemical oxidation.

CE 573. Treatment System Hydraulics
Hydraulic principles of water, domestic wastewater and industrial wastewater systems. Hydraulic analysis and design of collection, distribution and treatment systems and equipment. Topics covered include pipe and channel flow, pump characteristics and selection, friction loss, corrosion and material selection.

CE 574. Water Resources Management
This course provides an introduction to water resources engineering and management, with an emphasis on water resources protection and water supply. Course content addresses technical aspects as well as the legal, regulatory and policy aspects of water resources management. Topics include surface water hydrology and watershed protection, development of water supplies, conjunctive use of groundwater and surface water, management of reservoirs and rivers, the role of probability and statistics, systems analysis techniques, and planning of water resources projects.

CE 580. Advanced Project Management
This course develops an understanding of the managerial principles and techniques used throughout a construction project as they are applied to its planning, preconstruction and construction phases. The course emphasizes the integrative challenges of the human, physical and capital resources as experienced from the owner's point of view in the preconstruction phase of a project. Through assignments and case studies, the course reviews the complex environment of the construction industry and processes, project costing and economic evaluation, project organization, value engineering, time scheduling, contracting and risk allocation alternatives, contract administration, and cost and time control techniques. (Prerequisites: CE 3020, CE 3025, or equivalent.)

CE 582. Engineering and Construction Information Systems
This course provides an understanding of the various subjects involved in the use, design, development, implementation and maintenance of computer- based information systems in the construction industry. Theoretical and hands-on review of basic building blocks of information and decision support systems including user interfaces, database management systems, object-oriented approaches and multimedia. Applications include project scheduling and cost control, budgeting, project risk analysis, construction accounting, materials management and procurement systems, project document tracking and resource management. Commercial software—such as PRIMAVERA Project Planner, TIMBERLINE, and spreadsheets and databases—is extensively used. Students are required to complete a term project reviewing an existing information system and presenting recommendations for improvement. (Prerequisites: A knowledge of the material covered in CE 580 and CE 584 is expected). Course may be offered by special arrangement.

CE 583. Contracts and Law for Civil Engineers
An introduction to the legal aspects of construction project management, emphasis on legal problems directly applied to the practice of project management, contracts and specifications documents, codes and zoning laws, and labor laws.

CE 584. Advanced Cost Estimating Procedures
This course examines cost estimating as a key process in planning, designing and constructing buildings. Topics include the analysis of the elements of cost estimating; database development and management, productivity, unit costs, quantity surveys and pricing, and the application of these tools in business situations; marketing, sales, bidding, negotiating, value engineering, cost control, claims management and cost history. Computerization is evaluated as an enhancement to the process.

CE 586. Building Systems
This course introduces design concepts, components, materials and processes for major building projects. The topics analyze the choice of foundations, structures, building enclosures and other major building subsystems as affected by environmental and legal conditions, and market and project constraints. Consideration is given to the functional and physical interfaces among building subsystems. Emphasis is given to the processes through which design decisions are made in the evolution of a building project.

CE 587. Building Information Modeling (BIM)

This course introduces the concept of Building Information Modeling (BIM) which is a relatively new approach in planning, design, construction and operation of constructed facilities in a technologically enabled and collaborative fashion. The course reviews fundamental concepts for collaboration and integration; it also reviews technologies that support the BIM approach and provides discipline specific as well as global perspectives on BIM. The course format includes formal lectures, computer laboratory sessions, student presentations based on assigned readings and a project developed collaboratively by the students throughout the course. Guest speakers may be invited based on the topics covered and discussed in class.

Prerequisites: Basic knowledge of computers. Exposure to professional practice in any area of the Architecture / Engineering / Construction / Facilities Management (A/E/C/FM) industry is desirable. Students are not permitted to receive credit for CE 587 if they have previously received credit for CE 585 or CE 590A-BIM.

CE 590. Special Problems

(2 to 4 credits)

Individual investigations or studies of any phase of civil engineering as may be selected by the student and approved by the faculty member who supervises the work.

CE 591. Environmental Engineering Seminar

Participation of students in discussing topics of interest to environmental engineers.

CE 592. Constructed Facilities Seminar

Participation of students, faculty and recognized experts outside of WPI in developing modern and advanced topics of interest in the constructed facilities area.

CE 593. Advanced Project

This capstone project is intended for students completing the M.E. degree. The student is expected to identify all aspects of the M.E. curriculum and an integrative, descriptive systems approach. The project activity requires the student to describe the development, design construction, maintenance and operation process for an actual facility; to evaluate the performance of the facility with respect to functional and operational objectives; and to examine alternative solutions. Specific areas of study are selected by the student and approved by the faculty member. The work may be accomplished by individuals or small groups of students working on the same project. (Prerequisite: consent of instructor.)

CE 599. M.S. Thesis

Research study at the M.S. level.

CE 699. Ph.D. Thesis

Research study at the Ph.D. level.

Faculty

C. E. Wills, Professor and Department Head; Ph.D., Purdue, 1988. Distributed systems, networking, user interfaces.

E. O. Agu, Associate Professor; Ph.D., Massachusetts, 2001. Computer graphics, wireless networking, mobile computing and mobile health.

J. E. Beck, Associate Professor; Ph.D., Massachusetts, 2001. Machine learning, educational data mining, intelligent tutoring systems, human learning and problem solving.

D. C. Brown, Professor; Ph.D., Ohio State, 1984. Knowledge-based design systems, artificial intelligence.

M. L. Claypool, Professor; Ph.D., Minnesota, 1997. Distributed systems, networking, multimedia and online games.

D. J. Dougherty, Professor; Ph.D., Maryland, 1982. Logic in computer science, with a focus on security.

M. Y. Eltabakh, Associate Professor; Ph.D., Purdue University, 2010. Database management systems, information management.

K. Fisler, Professor; Ph.D., Indiana, 1996. Computer science education, formal methods, software security, and human factors in security.

M. A. Gennert, Professor; Sc.D., Massachusetts Institute of Technology, 1987. Image processing; image understanding; artificial intelligence; robotics.

T. Guo, Assistant Professor; Ph.D., University of Massachusetts Amherst, 2016. Distributed systems, cloud computing, data-intensive systems.

J. D. Guttman, Research Professor; Ph.D., Chicago, 1984. Information security, logic and formal methods, mechanized reasoning, programming languages.

L. Harrison, Assistant Professor; Ph.D., University of North Carolina at Charlotte, 2013. Information visualization, visual analytics, perception-based computation for visualization.

N. T. Heffernan, Professor; Ph.D., Carnegie Mellon, 2001. Intelligent tutoring agents, artificial intelligence, cognitive modeling, machine learning.

G. T. Heineman, Associate Professor; Ph.D., Columbia, 1996. Component-based software engineering, formal approaches to compositional design, design of algorithms.

M. Hofri, Professor; Ph.D., Technion (Israel), 1972. Analysis of algorithms, performance evaluation, applied probability, the use of statistics in algorithms, asymptotics.

X. Kong, Assistant Professor, Ph.D., University of Illinois, Chicago, IL 2014. Data mining, social networks, machine learning, big data analytics.

D. Korkin, Associate Professor, Ph.D., University of New Brunswick, Canada, 2003. Bioinformatics of disease, big data in biomedicine, computational genomics, systems biology, data mining, machine learning.

K. Lee, Assistant Professor; Ph.D., Texas A&M, 2013, Big data analytics and mining, social computing, and cybersecurity over large-scale networked information systems such as the Web, social media and crowd-based systems.

Y. Li, Assistant Professor, Ph.D., University of Minnesota, 2003. Big data from complex networks, large-scale network data measurement, online social behavior modeling, spectral graph theory.

C. Pinciroli, Assistant Professor, PhD., Université Libre de Bruxelles, Belgium, 2014. Swarm robotics, software engineering, multi-agent systems, human-swarm interaction, programming languages.

C. Rich, Professor; Ph.D., Massachusetts Institute of Technology, 1980. Artificial intelligence and its intersections with human-computer interaction, robotics, interactive media and game development.

C. Ruiz, Associate Professor; Ph.D., Maryland, 1996. Data mining, knowledge discovery in databases, machine learning.

E. A. Rundensteiner, Professor; Ph.D., University of California, Irvine, 1992. Data and information management, big data analytics, visual data discovery, stream and pattern mining, large scale data infrastructures.

G. N. Sarkozy, Professor; Ph.D., Rutgers, 1994. Graph theory, combinatorics, algorithms.

C. A. Shue, Associate Professor; Ph.D., Indiana, 2009. Computer networking, security, distributed systems.

C. L. Sidner, Research Professor; Ph.D., Massachusetts Institute of Technology, 1979. Discourse processing, collaboration, human-robot interaction, intelligent user interfaces, natural language processing, artificial intelligence.

K. Venkatasubramanian, Assistant Professor; Ph.D., Arizona State, 2009. Secure cyber-physical systems, body area networks, trust management, medical device security.

R. J. Walls, Assistant Professor; Ph.D., University of Massachusetts Amherst, 2014. Systems security and privacy, digital forensics and online crime, large-scale internet measurement.

J. R. Whitehill, Assistant Professor; Ph.D., University of California, San Diego, 2012. Machine learning, crowdsourcing, automated teaching, human behavior recognition.

Research Interests

The current departmental activities include, among other areas, analysis of algorithms, applied logic, artificial intelligence, big data, computer vision, computer graphics, database and information systems, data mining, distributed systems, graph theory and computational complexity, intelligent tutoring systems, machine learning, network performance evaluation, programming languages, robotics, security, software engineering, user interfaces, virtual reality, visualization, and Web-based systems. Research groups meet weekly and focus on topics related to the above areas. Students are encouraged to

participate in the meetings related to their area(s) of interest. Research and development projects and theses are available in these areas. Computer science students may also participate in computer applications research work being conducted in a number of other departments including electrical and computer engineering, mechanical engineering, biomedical and fire protection engineering. Students are also encouraged to undertake projects and theses in cooperation with neighboring computer manufacturers or commercial organizations.

Programs of Study

Graduate programs in Computer Science provide opportunities for advanced coursework and research for highly qualified students. Graduate Certificates, recognizing completion of a cohesive set of advanced courses, are offered in several areas of Computer Science. The Master of Science degree is more comprehensive; with thesis and non-thesis (coursework-only) options, it is the degree of choice for many full-time students and working professionals. The Doctor of Philosophy degree emphasizes deeper study and discovery in preparation for a career in research or education.

Graduate programs may be undertaken on a full-time or part-time basis. For all students, challenging courses and demanding research projects, with high expectations of accomplishment, are the standard.

Admission Requirements

Applicants are expected to demonstrate sufficient background in core Computer Science for graduate-level work. Background in both theoretical and applied Computer Science, with significant programming experience and some college-level mathematics, is required. A bachelor's degree in Computer Science or a closely related field should be adequate preparation. Students from other backgrounds are welcome to apply if they can demonstrate their readiness through other means, such as the Computer Science GRE Subject exam. Work experience will be considered if it covers a broad spectrum of Computer Science at a technical or mathematical level.

A student may apply to the Ph.D. program upon completion of either a bachelor's (*in which case the master's degree must first be completed as part of the Ph.D. studies*) or master's degree in computer science, or with an equivalent background.

Non-matriculated students may enroll in up to two courses prior to applying for admission to a Computer Science Graduate Program.

Certificate Programs

WPI's Graduate Certificate Program provides an opportunity for students holding undergraduate degrees to continue their study in an advanced area. A B.S. or B.A. degree is the general requirement. Certificate programs require a student to complete 4-5 thematically related courses in their area of interest. Each student's program of study must be approved by the academic advisor. Academic advisors are assigned upon admission to the program but may be changed in accordance with departmental policies.

Details about the certificates available in the Department of Computer Science can be found online at https://www.wpi.edu/academics/study/computer-science-certificate

Degree Requirements

For the M.S.

The M.S. program in Computer Science requires 33 credit hours of work. Students may select a non-thesis option or a thesis-option, which requires a 9-credit thesis. Each student should carefully weigh the pros and cons of these alternatives in consultation with his or her advisor prior to selecting an option, typically in the second year of study. The department will allow a student to change options only once. All entering students must submit a plan of study identifying the courses to be taken. The plan of study must be approved by the student's advisor and the CS Graduate Coordinator, and must include the following minimum requirements:

1. Computer Science Breadth Requirement (12 credits)

M.S. students are required to achieve a passing grade in courses from four different bins, including at least three essential bins. The eleven bins are listed below, together with their corresponding courses.

Essential Bins (9 credits)

- **Theory** (3 credits): 5003, 503, 521, 559
- **Algorithms** (3 credits): 5084, 584, 504
- One course from either Bin: (3 credits)
  - **Systems**: 502, 533, 535
  - **Networks**: 513, 528, 529, 530, 577, 558

Breadth Bins (3 credits)

- **Design**: 509, 546, 562
- **Compilers/Languages**: 536, 544
- **Graphics/Imaging**: 543, 545, 549, 563, 573
- **AI**: 534, 538, 539, 540, 548, 549, 566
- **Databases**: 542, 561, 585, 586
- **Cybersecurity**: 557, 558, 564, 571, 578
- **Applications of CS**: 526, 565, 567, 568, 582, 583

Courses with a 5000 number (e.g., 5003, 5084) are preparatory courses, designed specifically for students with insufficient background knowledge or skills. Graduate credit can be earned for these course and M.S. students may use them to satisfy bin requirements. However, students with a solid undergraduate degree in CS are strongly encouraged to take more advanced courses within the bins. *Note: B.S./M.S. students may satisfy this breadth requirement with fewer than 12 credits because of the credit conversion rate as described on page 22.*

2. Computer Science Electives (21 credits)

M.S. students must complete sufficient course work selected from CS courses at the 500-level or independent study. With the permission of the academic advisor, a student may take a total of at most six graduate credits from outside of Computer Science towards the M.S. degree. Courses in college teaching may not be counted towards the 33 credits required for a CS Master's degree.

Thesis Option

A thesis consisting of a research or development project worth a minimum of 9 credit hours must be completed and presented to the faculty. A thesis proposal must be approved by the department by the end of the semester in which a student has registered for a third thesis credit. Proposals will be considered only at regularly scheduled department meetings.

Students funded by a teaching assistantship, research assistantship or fellowship must complete the thesis option.

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Non-thesis Option

A total of at least 33 credit hours must be satisfactorily completed, including four courses which satisfy the Breadth Requirement. Students should endeavor to take these four courses as early as possible so as to provide the background for the remaining graduate work.

Non-thesis option is not applicable to students funded by a teaching assistantship, research assistantship or fellowship.

For the Ph.D.

Students are advised to contact the department for detailed rules, as there are departmental guidelines, in addition to the university's requirements, for the Ph.D. degree.

Upon admission, the student is assigned an academic advisor and together they design a Plan of Study during the first semester of the student's Ph.D. program.

The student must satisfy the Ph.D. Qualifying Requirement, consisting of the Breadth Requirement and the Research Qualifying Requirement. These requirements are described in the Graduate Regulations on the CS department website http://web.cs.wpi.edu/Intranet/Graduate/guide.html.

Upon successful completion of the Ph.D. qualifying requirement, the student becomes a computer science Ph.D. candidate. The student's Dissertation Committee must be formed within the first year of candidacy. The student selects a research advisor from within the CS department, and together they select, with the approval of the CS Graduate Committee, three additional members, at least one of whom must be from outside the WPI CS department. The Dissertation Committee will be responsible for supervising the comprehensive examination, and approving the dissertation proposal and final report.

The Ph.D. degree requirements consist of a coursework component and a research component, which together must total at least 60 credit hours beyond the master's degree requirement. The coursework component consists of at least 27 graduate credits, including 3 credits of graduate level mathematics. These 27 coursework credits must contain at least 15 graduate credits in computer science. Coursework credits taken outside computer science must be approved by the student's advisor.

The student may also enroll for research credits, but is only allowed up to 18 research credits prior to the acceptance of the written dissertation proposal by the Dissertation Committee. With the approval of the Dissertation Committee, the student applies for and takes the Ph.D. comprehensive examination. This examination must be passed prior to the completion of the dissertation defense and is normally taken after some initial dissertation research has been performed. With approval of the Dissertation Committee, the student applies for and takes the dissertation proposal examination, usually within one year of the Ph.D. candidacy.

The Ph.D. research component consists of at least 30 credits (including any research credits earned prior to the acceptance of the dissertation proposal and excluding any research credits applied toward a master's degree) leading to a dissertation and a public defense, which must be approved by the student's Dissertation Committee.

Ph.D. Breadth Requirements

Ph.D. students are required to achieve at least a B grade in courses from six different bins (listed earlier in the CS Breadth Requirement for the M.S. Degree). These six bins must include all three essential bins. Students must achieve an A grade in at least four of the six bins, including an A grade in at least one essential bin.

Courses with a 5000 number (e.g., 5003, 5084) are "preparatory courses", designed specifically for students with insufficient background knowledge or skills. While graduate credit can be earned for these courses, they cannot be used by Ph.D. students to satisfy a bin requirement.

The Ph.D. breadth requirement must be satisfied by the time the student achieves the following number of graduate credits: for PhD-90: 54 credits (18 courses); for PhD-60: 36 credits (12 courses).

Students admitted to the CS Ph.D. program with only a bachelor's degree (i.e., PhD-90) must complete a CS MS degree as the first step towards the Ph.D. However, the Ph.D. breadth requirement is more demanding than the MS breadth requirement. Consequently, those students should satisfy the Ph.D. breadth requirement instead while obtaining the MS degree. All other requirements for the M.S. degree remain the same.

B.S./M.S. Program

Overview

The university rules for the B.S./M.S. program are described in Section 5 of the undergraduate catalog and on page 22 of the graduate catalog.

Process

Students may formally apply for admission to the B.S./M.S. program during or after taking their second 4000-level Computer Science course. Forms are available through the graduate admissions office or via their website.

Students who have entered the B.S./M.S. program, or are considering it, qualify for B.S./M.S. credit for the courses listed below.

In order to receive B.S./M.S. credit for a course, the student must complete a Course Selection Form; the instructor will indicate the conditions that the student must satisfy in order to receive B.S./M.S. credit for the course, such as earning a specific grade or doing additional assigned work. Faculty may offer, at their discretion, an additional 1/6 undergraduate unit, or equivalently a 1 graduate credit, for completing additional work in the course. To obtain this credit, the student must register for 1/6 undergraduate unit of independent study at the 4000-level or a 1 graduate credit independent study at the 500-level, with permission from the instructor.

Regulations

The CS department allows only selected 4000-level undergraduate course credits to count towards the B.S./M.S. The CS 4000-level course credits that may be counted towards both degrees are:

- 4100, 4120, 4123, 4233, 4241, 4341, 4401, 4404, 4432, 4445, 4513, 4515, 4516, 4518, 4533, 4536, 4731, 4732
- 4000-level Undergraduate Independent Studies, with permission of instructor and either the Graduate Committee or the Department Chair

Some undergraduate and graduate courses cover similar material. Students may receive credit for both when the graduate course covers extensive material beyond the undergraduate course. The table below lists courses with significant overlap. A student can receive credit for at most one of the two courses in any row of this table.

Undergraduate Course	Graduate Course
CS 4341 Introduction to Artificial Intelligence	CS 534 Artificial Intelligence
CS 4432 Database Systems II	CS 542 Database Management Systems
CS 4445 Data Mining and Knowledge Discovery in Databases	CS 548 Knowledge Discovery and Data Mining
CS 4513 Distributed Systems	CS 502 Operating Systems
CS 4516 Advanced Computer Networks	CS 513 Computer Networks
CS 4518 Mobile and Ubiquitous Computing	CS 528 Mobile and Ubiquitous Computing
CS 4533 Techniques of Programming Language Translation	CS 544 Compiler Construction
CS 4536 Programming Languages	CS 536 Programming Language Design
CS 4731 Computer Graphics	CS 543 Computer Graphics
CS 4803 Biological and Biomedical Database Mining	CS 583 Biological and Biomedical Database Mining

A B.S./M.S. student may use 1/3 unit of undergraduate credit or independent study/project work taken for B.S./M.S. credit to satisfy a bin requirement, if any of the following conditions is met: (1) The undergraduate course covers material similar to that of a graduate course that satisfies the bin. The table above provides pairs of undergraduate and graduate courses that cover similar material. The undergraduate course under consideration must appear in this table, and the corresponding graduate course must satisfy the bin requirement. (2) The course or independent study/project work is deemed to satisfy the bin by the instructor, Bin Committee, and Graduate Program Chair as indicated on the Graduate Bins Petition Form. (3) B.S./M.S. students that receive B.S./M.S. credit for one of the following courses can use that course to satisfy the corresponding bin.

- **Theory**: 4123 (Theory of Computation)
- **Algorithms**: 4120 (Analysis of Algorithms)
- **Design**: 4233 (OOAD), 4241 (Webware)
- **Graphics/Imaging**: 4732 (Animation)
- **Cyber Security**: 4401 (Software Security), 4404 (Tools and Techniques)
- **Applications of CS**: 4100 (AI for IMGD)

Facilities

WPI boasts excellent computing resources and network connectivity through the university's Computing & Communications Center and the CS Department's own systems. A wide range of machines provides web, mail, file, high-performance computation, and security services. An extensive software library is available free of charge to all campus users. Other specialized resources include multiple high performance and parallel-computing clusters. WPI is a member of the Internet2 consortium and WPI's campus network consists of a 10 Gigabit (on campus) backbone with multiple connections to the global internet. High speed wireless connectivity is available virtually everywhere on campus.

Computer Science Research Groups/Laboratories

Applied Logic and Security Group (ALAS) Lab

Profs. Dougherty, Fisler, Guttman, Shue, Venkatasubramanian & Wills

The ALAS group explores various problems related to security and applied logic, including research on privacy, network security, software engineering, software verification, security, and programming languages.

Artificial Intelligence Research Group (AIRG)

Profs. Beck, Berenson, Brown, Gennert, Heffernan, Rich, Ruiz & Sidner

AIRG members share interests in the theory and applications of knowledge-based systems. Current research includes intelligent tutoring systems, intelligent design, machine learning, data mining, robotics, multi-agent systems, and intelligent interfaces.

Database Systems Research Group (DSRG) Lab

Profs. Rundensteiner, Eltabakh, Kong & Li

This group focuses on research issues and project work related to very large database and information systems in support of advanced applications including business, engineering, and sciences. Currently on-going projects include intelligent event analytics, scalable data stream processing systems, map-reduce technologies, biological databases, stream mining and discovery, large-scale visual information exploration, medical process tracking, and distributed heterogeneous information sources.

Human-Robot Interaction (HRI) Lab

Profs. Rich & Sidner

If human-like robots are ever going to move freely among us, we will need to understand how to program them to collaborate with us smoothly and naturally. Our research spans robotics, artificial intelligence, computational linguistics and human-computer interaction.

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Knowledge Discovery and Data Mining (KDDRG) Lab

Profs. Ruiz, Kong & Li

KDDRG conducts research in data mining, machine learning, and knowledge discovery in databases. Current research projects include applications of data mining to clinical medicine, genomic data, sequence mining, and web mining.

Mobile Graphics Research Group (MGRG)

Prof. Agu

MGRG is investigating architectures and techniques that enable high-end servers to assist heterogeneous mobile hosts in rendering large geometric models. Wireless networked graphics applications are becoming more pervasive on mobile devices. Computer graphics applications are computationally intensive and resource hungry, while mobile devices have limited resources, low bandwidths and high error rates.

Performance Evaluation of Distributed Systems (PEDS) Lab

Profs. Agu, Claypool, Shue & Wills

PEDS is interested in the design and analysis of distributed systems, with a special focus on the performance of distributed operating systems.

Software Engineering Research Group (SERG)

Profs. Heineman, Fisler & Rundensteiner

SERG meets to discuss issues related to the discipline of Software Engineering. SERG has several goals: to provide a forum for discussion of the research of group members; to attract graduate students and prospective MQPs in Software Engineering; and to generate new areas of software engineering research.

Theory Umbrella Group (THUG)

Profs. Dougherty, Fisler, Guttman & Selkow

THUG is a group dedicated to the discussion of theory. The group meets each week for the Theory Seminar, which features talks on all aspects of theoretical computer science. Students and faculty in all areas of computer science are welcome to participate.

Tutor Research Group (TRG) Lab

Profs. Beck & Heffernan

TRG researches intelligent tutoring systems and tutoring strategies. Topics include artificial intelligence, machine learning, educational data mining, and cognitive science.

Off-Campus Research Opportunities

Computer science graduate students have opportunities for research and development in cooperation with several neighboring organizations, both for the master's thesis and Ph.D. dissertation. These and other opportunities provide real-world problems and experiences consistent with WPI's policy of extending learning beyond the classroom.

Course Descriptions

All courses are 3 credits unless otherwise noted.

CS 5003. Foundations of Computer Science: an Introduction

This is the study of mathematical foundations of computing, at a slower pace than that of CS 503 and with correspondingly fewer background assumptions. Topics include finite automata and regular languages, pushdown automata and context-free languages, Turing machines and decidability, and an introduction to computational complexity. (Prerequisite: an undergraduate course in discrete mathematics.)

CS 5007. Introduction to Applications of Computer Science with Data Structures and Algorithms

This is an introductory graduate course teaching core computer science topics typically found in an undergraduate Computer Science curriculum, but at a graduate-level pace. It is primarily intended for students with little formal preparation in Computer Science to gain experience with fundamental Computer Science topics.

After a review of programming concepts the focus of the course will be on data structures from the point of view of the operations performed upon the data and to apply analysis and design techniques to non-numeric algorithms that act on data structures. The data structures covered include lists, stacks, queues, trees and graphs. Projects will focus on the writing of programs to appropriately integrate data structures and algorithms for a variety of applications.

This course may not be used to satisfy degree requirements for a B.S., M.S., or Ph.D. degree in Computer Science or a minor in Computer Science. It may satisfy the requirements for other degree programs at the discretion of the program review committee for the particular degree. (Prerequisites: Experience with at least one high-level programming language such as obtained in an undergraduate programming course.)

CS 502. Operating Systems

The design and theory of multiprogrammed operating systems, concurrent processes, process communication, input/output supervisors, memory management, resource allocation and scheduling are studied. (Prerequisites: knowledge of computer organization and elementary data structures, and a strong programming background.)

CS 503. Foundations of Computer Science

This is the study of mathematical foundations of computing. Topics include finite automata and regular languages, pushdown automata and context-free languages, Turing machines and decidability, and an introduction to computational complexity. (Prerequisites: Knowledge of discrete mathematics and algorithms at the undergraduate level, and some facility with reading and writing mathematical proofs.)

CS 504. Analysis of Computations and Systems

The following tools for the analysis of computer programs and systems are studied: probability, combinatorics, the solution of recurrence relations and the establishment of asymptotic bounds. A number of algorithms and advanced data structures are discussed, as well as paradigms for algorithm design. (Prerequisites: CS 5084 or equivalent.)

CS 505. Social Implications of Computing

This course is concerned with the effects of computer technology on society. It will explore a wide range of topics including privacy, liability, proprietary protection, the effects of artificial intelligence on humanity's view of itself and globalization. It will also consider the issues of professional ethics and professional responsibility, as well as discrimination in the workplace, in education and in user interfaces. Papers, presentations, discussions, extensive readings and a course project are possible components of this course. (Prerequisites: a college degree and either two computer science classes or a year's experience in the computer industry including sales and management.)

CS 5084. Introduction to Algorithms: Design and Analysis

This course is an introduction to the design, analysis and proofs of correctness of algorithms. Examples are drawn from algorithms for many areas. Analysis techniques include asymptotic worst case and average case, as well as amortized analysis. Average case analysis includes the development of a probability model. Techniques for proving lower bounds on complexity are discussed, along with NP-completeness. Prerequisites: an undergraduate knowledge of discrete mathematics and data structures. *Note: students with a strong background in design and analysis of computer systems, at the level equal to a B.S. in computer science, should not take CS 5084 and should consider taking CS 504 or CS 584.*

CS 509. Design of Software Systems

This course introduces students to a methodology and specific design techniques for team-based development of a software system. Against the backdrop of the software engineering life-cycle, this course focuses on the object-oriented paradigm and its supporting processes and tools. Students will be exposed to industrial-accepted standards and tools, such as requirements elicitation, specification, modeling notations, design patterns, software architecture, integrated development environments and testing frameworks. Students will be expected to work together in teams in the complete specification, implementation and testing of a software application. Prerequisites: knowledge of a recursive high-level language and data structures. An undergraduate course in software engineering is desirable.

CS 513. Computer Networks

This course provides an introduction to the theory and practice of the design of computer and communications networks, including the ISO seven-layer reference model. Analysis of network topologies and protocols, including performance analysis, is treated. Current network types including local area and wide area networks are introduced, as are evolving network technologies. The theory, design and performance of local area networks are emphasized. The course includes an introduction to queueing analysis and network programming. (Prerequisites: knowledge of the C programming language is assumed. CS 504 or equivalent background in CS 5084 or CS 584.)

CS 514/ECE 572. Advanced Systems Architecture

See ECE 572 course description on page 102.

CS 521. Logic in Computer Science

This course is an introduction to mathematical logic from a computer science perspective. Topics covered include the exploration of model theory, proof theory, and decidability for propositional and first-order classical logics, as well as various non-classical logics that provide iseful tools for computer science (such as temporal and intuitionistic logics). The course stresses the application of logic to various areas of computer science such as computability, theorem proving, programming languages, specification,and verification. The specific applications included will vary by instructor. (Prerequisites: CS 503, or equivalent background in basic models of computation.)

CS 522/MA 510. Numerical Methods

See MA 510 course description.

CS 525. Topics in Computer Science

A topic of current interest is covered in detail. Please consult the department for a current listing of selected topics in this area. (Prerequisites: vary with topic.)

CS/RBE 526. Human-Robot Interaction

This course focuses on human-robot interaction and social robot learning, exploring the leading research, design principles and technical challenges we face in developing robots capable of operating in real-world human environments. The course will cover a range of multidisciplinary topics, including physical embodiment, mixed-initiative interaction, multi-modal interfaces, human-robot teamwork, learning algorithms, aspects of social cognition, and long-term interaction. These topics will be pursued through independent reading, class discussion, and a final project. (Prerequisites: Mature programming skills and at least undergraduate level knowledge of Artificial Intelligence, such as CS 4341. No hardware experience is required.)

CS 528. Mobile and Ubiquitous Computing

This course acquaints participants with the fundamental concepts and state-of-the-art computer science research in mobile and ubiquitous computing. Topics covered include mobile systems issues, human activity and emotion sensing, location sensing, mobile HCI, mobile social networking, mobile health, power saving techniques, energy and mobile performance measurement studies and mobile security. The course consists of weekly presentations on current advanced literature, discussions and a term project. The term project involves implementing research ideas on a mobile device such as a smartphone. (Prerequisite: CS 502 or an equivalent graduate level course in Operating Systems, and CS 513 or an equivalent graduate level course in Computer Networks, and proficiency in a high level programming language.)

CS 529. Multimedia Networking

This course covers basic and advanced topics related to using computers to support audio and video over a network. Topics related to multimedia will be selected from areas such as compression, network protocols, routing, operating systems and human computer interaction. Students will be expected to read assigned research papers and complete several programming intensive projects that illustrate different aspects of multimedia computing. (Prerequisites: CS 502 and CS 513 or the equivalent and strong programming skills.)

CS 533/ECE 581. Modeling and Performance Evaluation of Network and Computer Systems

Methods and concepts of computer and communication network modeling and system performance – evaluation. Stochastic processes; measurement techniques; monitor tools; statistical analysis of performance experiments; simulation models; analytic modeling and queueing theory; M/M, Erlang, G/M, M/G, batch arrival, bulk service and priority systems; work load characterization; performance evaluation problems. (Prerequisites: CS 5084 or CS 504 or equivalent background in probability and some background in statistics.)

CS 534. Artificial Intelligence

This course gives a broad survey of artificial intelligence. The course will cover methods from search, probabilistic reasoning, and learning, among other topics. Selected topics involving the applications of these tools are investigated. Such topics might include natural language understanding, scene understanding, game playing, and planning. (Prerequisites: familiarity with data structures and a high-level programming language.)

CS 535. Advanced Topics in Operating Systems

This course discusses advanced topics in the theory, design and implementation of operating systems. Topics will be selected from such areas as performance of operating systems, distributed operating systems, operating systems for multiprocessor systems and operating systems research. (Prerequisites: CS 502 and either CS 5084, CS 504, CS 584, or equivalent background in probability.)

CS 536. Programming Language Design

This course discusses the fundamental concepts and general principles underlying current programming languages and models. Topics include control and data abstractions, language processing and binding, indeterminacy and delayed evaluation, and languages and models for parallel and distributed processing. A variety of computational paradigms are discussed: functional programming, logic programming, object-oriented programming and data flow programming. (Prerequisites: student is expected to know a recursive programming language and to have an undergraduate course in data structures.)

CS 538. Knowledge-Based Systems

The course will review knowledge-based problem-solving systems. It will concentrate on an analysis of their architecture, knowledge and problem-solving style in order to classify and compare them. An attempt will be made to evaluate the contribution to our understanding of problems that such systems can tackle. (Prerequisite: CS 534 or equivalent or permission of the instructor.)

CS 539. Machine Learning

The focus of this course is machine learning for knowledge-based systems. It will include reviews of work on similarity-based learning (induction), explanation-based learning, analogical and case-based reasoning and learning, and knowledge compilation. It will also consider other approaches to automated knowledge acquisition as well as connectionist learning. (Prerequisite: CS 534 or equivalent, or permission of the instructor.)

CS 540. Artificial Intelligence in Design

The main goal of this course is to obtain a deeper understanding of what "design" is, and how AI might be used to support and study it. Students will examine some of the recent AI-based work on design problem-solving. The course will be run in seminar style, with readings from the current literature and with student presentations. The domains will include electrical engineering design, mechanical engineering design, civil engineering

design and software design (i.e., automatic programming). This course will be of interest to those wanting to prepare for research in design, or those wishing to increase their understanding of expert systems. Graduate students from departments other than computer science are welcome. (Prerequisite: knowledge of artificial intelligence is required. This can only be waived with permission of the instructor).

CS 542. Database Management Systems

An introduction to the theory and design of data-base management systems. Topics covered include internals of database management systems, fundamental concepts in database theory, and database application design and development. In particular, logical design and conceptual modeling, physical database design strategies, relational data model and query languages, query optimization, transaction management and distributed databases. Typically there are hands-on assignments and/or a course project. Selected topics from the current database research literature may be touched upon as well. (Prerequisite: CS 5084 would be helpful.)

CS 543. Computer Graphics

This course examines typical graphics systems, both hardware and software; design of low-level software support for raster displays; 3-D surface and solids modeling; hidden line and hidden surface algorithms; and realistic image rendering including shading, shadowing, reflection, refraction and surface texturing. (Prerequisites: familiarity with data structures, a recursive high-level language and linear algebra. CS 509 would be helpful.)

CS 544. Compiler Construction

A general approach to the design of language processors is presented without regard for either the source language or target machine. All phases of compilation and interpretation are investigated in order to give the student an appreciation for the overall construction of a compiler. Typical projects may include implementation of a small compiler for a recursive or special-purpose language. (Prerequisites: knowledge of several higher-level languages and at least one assembly language. The material in CS 503 is helpful.)

CS 545/ECE 545. Digital Image Processing

This course presents fundamental concepts of digital image processing and an introduction to machine vision. Image processing topics will include visual perception, image formation, imaging geometries, image transform theory and applications, enhancement, restoration, encoding and compression. Machine vision topics will include feature extraction and representation, stereo vision, model-based recognition, motion and image flow, and pattern recognition. Students will be required to complete programming assignments in a high-level language. (Prerequisites: working knowledge of undergraduate level signal analysis and linear algebra; familiarity with probability theory is helpful but not necessary.)

CS 546. Human-Computer Interaction

This course prepares graduate students for research in human-computer interaction. Topics include the design and evaluation of interactive computer systems, basic psychological considerations of interaction, interactive language design, interactive hardware design and special input/output techniques. Students are expected to present and review recent research results from the literature, and to complete several projects. (Prerequisites: students are expected to have mature programming skills. Knowledge of software engineering would be an advantage.)

CS 548. Knowledge Discovery and Data Mining

This course presents current research in Knowledge Discovery in Databases (KDD) dealing with data integration, mining, and interpretation of patterns in large collections of data. Topics include data warehousing and data preprocessing techniques; data mining techniques for classification, regression, clustering, deviation detection, and association analysis; and evaluation of patterns minded from data. Industrial and scientific applications are discussed. Recommended background: Background in artificial intelligence, databases, and statistics at the undergraduate level, or permission of the instructor. Proficiency in a high level programming language.

CS/RBE 549. Computer Vision

This course examines current issues in the computer implementation of visual perception. Topics include image formation, edge detection, segmentation, shape-from-shading, motion, stereo, texture analysis, pattern classification and object recognition. We will discuss various representations for visual information, including sketches and intrinsic images. (Prerequisites: CS 534, CS 543, CS 545, or the equivalent of one of these courses.)

CS 557. Software Security Design and Analysis

Software is responsible for enforcing many central security goals in computer systems. These goals include authenticating users and other external principals, authorizing their actions, and ensuring the integrity and confidentiality of their data. This course studies how to design, implement, and analyze mechanisms to enforce these goals in both web systems and programs in traditional languages. Topics include: identifying programming choices that lead to reliable or flawed security outcomes, successful and unsuccessful strategies for incorporating cryptography into software, and analysis techniques that identify security vulnerabilities. The course will cover both practical and theoretical aspects of secure software, and will include a substantial secure software design project. (Prerequisites: Programming and software engineering experience (commensurate with an undergraduate Computer Science major), and background in foundational models of computing systems (on par with CS 5003 or CS 503).)

CS 558. Computer Network Security

This course covers core security threats and mitigations at the network level. Topics include: denial-of-service, network capabilities, intrusion detection and prevention systems, worms, botnets, Web attacks, anonymity, honeypots, cybercrime (such as phishing), and legality and ethics. The course prepares students to think broadly and concretely about network security; it is not designed to teach students low-level tools for monitoring or maintaining system security. Assignments and projects will assess each student's ability to think both conceptually and practically about network security. (Prerequisites: a strong background in computer networking and systems, either at the undergraduate or graduate level, and moderate programming experience.)

CS 559. Advanced Topics in Theoretical Computer Science

This course has an instructor-dependent syllabus.

CS 561. Advanced Topics in Database Systems

This course covers modern database and information systems as well as research issues in the field. Topics and systems covered may include object-oriented, workflow, active, deductive, spatial, temporal and multimedia databases. Also discussed will be recent advances in database systems such as data mining, on-line analytical processing, data warehousing, declarative and visual query languages, multimedia database tools, web and unstructured data sources, and client-server and heterogeneous systems. The specific subset of topics for a given course offering is selected by the instructor. Research papers from recent journals and conferences are used. Group project required. (Prerequisites: CS 542 or equivalent. Expected background includes a knowledge of relational database systems.)

CS 562. Advanced Topics in Software Engineering

This course focuses on the nondesign aspects of software engineering. Topics may include requirements specification, software quality assurance, software project management and software maintenance. (Prerequisite: CS 509.)

CS 564. Advanced Topics in Computer Security

This course examines one or more selected current issues in the area of computer security. Specific topics covered are dependent on the instructor. Potential topics include: modeling and analyzing security protocols, access-control, network security, and human-centered security. (Prerequisites: a graduate level security course or equivalent experience.

CS/SEME 565. User Modeling

User modeling is a cross-disciplinary research field that attempts to construct models of human behavior within a specific computer environment. Contrary to traditional artificial intelligence research, the goal is not to imitate human behavior as such, but to make the machine able to understand the expectations, goals, knowledge, information needs, and desires of a user in terms of a specific computing environment. The computer representation of this information about a user is called a user model, and systems that construct and utilize such models are called user modeling systems. A simple example of a user model would be an e-commerce site which makes use of the user's and similar users' purchasing and browsing behavior in order to better understand the user's preferences. In this class, the focus is on obtaining a general understanding of user modeling, and an understanding of how to apply user modeling techniques. Students will read seminal papers in the user modeling literature, as well as complete a course project where students build a system that explicitly models the user. (Prerequisites: Knowledge of probability.)

CS/SEME 566. Graphical Models for Reasoning Under Uncertainty

This course will introduce students to graphical models, such as Bayesian networks, Hidden Markov Models, Kalman filters, particle filters, and structural equation models. Graphical models are applicable in a wide variety of work in computer science for reasoning under uncertainty such as user modeling, speech recognition, computer vision, object tracking, and determining a robot's location. This course will cover 1) using data to estimate the parameters and structure of a model using techniques such as expectation maximization, 2) understanding techniques for performing efficient inference on new observations such as junction trees and sampling, and 3) learning about evaluation techniques to determine whether a particular model is a good one. (Prerequisites: CS 534 Artificial Intelligence or permission of the instructor.)

CS/SEME 567. Empirical Methods for Human-Centered Computing

This course introduces students to techniques for performing rigorous empirical research in computer science. Since good empirical work depends on asking good research questions, this course will emphasize creating conceptual frameworks and using them to drive research. In addition to helping students understand what makes a good research question and why, some elementary statistics will be covered. Furthermore, students will use and implement computationally intensive techniques such as randomization, bootstrapping, and permutation tests. The course also covers experiments involving human subjects, and some of the statistical and non-statistical difficulties researchers often encounter while performing such work (e.g., IRB (Institutional Review Board), correlated trials, and small sample sizes). While this course is designed for students in Human Computer Interaction, Interactive Media & Game Development, and Learning Sciences and Technologies, it is appropriate for any student with programming experience who is doing empirical research. (Prerequisites: MA 511 Applied Statistics for Engineers and Scientists or permission of instructor.)

CS/SEME 568. Artificial Intelligence for Adaptive Educational Technology

Students will learn how to enable educational technology to adapt to the user and about typical architectures used by existing intelligent tutoring systems for adapting to users. Students will see applications of decision theoretic systems, reinforcement learning, Markov models for action selection, and Artificial Intelligence (AI) planning. Students will read papers that apply AI techniques for the purpose of adapting to users. Students will complete a project that applies these techniques to build an adaptive educational system. (Prerequisites: CS 534 Artificial Intelligence or permission of the instructor.)

CS 571. Case Studies in Computer Security

This course examines security challenges and failures holistically, taking into account technical concerns, human behavior, and business decisions. Using a series of detailed case studies, students will explore the interplay among these dimensions in creating secure computing systems and infrastructure. Students will also apply lessons from the case studies to emerging secure-systems design problems. The course requires active participation in class discussions, presentations, and writing assignments. It does not involve programming, but assumes that students have substantial prior experience with security protocols, attacks, and mitigations at the implementation level. This course satisfies the behavioral component of the M.S. specialization in computer security. (Prerequisites: A prior course or equivalent experience in technical aspects of computer security, at either the software or systems level.)

CS 573. Data Visualization

This course exposes students to the field of data visualization, i.e., the graphical communication of data and information for the purposes of presentation, confirmation, and exploration. The course introduces the stages of the visualization pipeline. This includes data modeling, mapping data attributes to graphical attributes, visual display techniques, tools, paradigms, and perceptual issues. Students learn to evaluate the effectiveness of visualizations for specific data, task, and user types. Students implement visualization algorithms and undertake projects involving the use of commercial and public-domain visualization tools. Students also read papers from the current visualization literature and do classroom presentations. (Prerequisite: a graduate or undergraduate course in computer graphics.)

CS 577/ECE 537. Advanced Computer and Communications Networks

This course covers advanced topics in the theory, design and performance of computer and communications networks. Topics will be selected from such areas as local area networks, metropolitan area networks, wide area networks, queueing models of networks, routing, flow control, new technologies and protocol standards. The current literature will be used to study new networks concepts and emerging technologies. (Prerequisite: CS 533/ECE 581 and either CS 513 or ECE 506)

CS 578/ECE 578. Cryptography and Data Security

See ECE 578 course description.

CS 582/BCB 502. Biovisualization

This course uses interactive visualization to explore and analyze data, structures, and processes Topics include the fundamental principles, concepts, and techniques of visualization and how visualization can be used to analyze and communicate data in domains such as biology. Students will be expected to design and implement visualizations to experiment with different visual mappings and data types, and will complete a research oriented project. Prerequisite: experience with programming (especially JavaScript), databases, and data structures. Students may not receive credit for both CS 582 and CS 4802.

CS 583/BCB 503. Biological and Biomedical Database Mining

This course will investigate computational techniques for discovering patterns in and across complex biological and biomedical sources including genomic and proteomic databases, clinical databases, digital libraries of scientific articles, and ontologies. Techniques covered will be drawn from several areas including sequence mining, statistical natural language processing and text mining, and data mining. (Prerequisite: strong programming skills, an undergraduate or graduate course in algorithms, an undergraduate course in statistics, and one or more undergraduate biology courses.) Students may not receive credit for both CS 583 and CS 4803.

CS 584. Algorithms: Design and Analysis

This covers the same material as CS5084 though at a more advanced level. As background, students should have experience writing programs in a recursive, high-level language and should have the background in mathematics that could be expected from a B.S. in Computer Science.

CS 585/DS 503. Big Data Management

Big Data Management deals with emerging applications in science and engineering disciplines that generate and collect data at unprecedented speed, scale, and complexity that need to be managed and analyzed efficiently. This course introduces the latest techniques and infrastructures developed for big data management including parallel and distributed database systems, map-reduce infrastructures, scalable platforms for complex data types, stream processing systems, and cloud-based computing. Query processing, optimization, access methods, storage layouts, and energy management techniques developed on these infrastructures will be covered. Students are expected to engage in hands-on projects using one or more of these technologies. Prerequisites: A beginning course in databases at the level of CS 4432 or equivalent knowledge, and programming experience.

CS 586/DS 504. Big Data Analytics

Big Data Analytics addresses the obstacle that innovation and discoveries are no longer hindered by the ability to collect data, but by the ability to summarize, analyze, and discover knowledge from the collected data in a scalable fashion. This course covers computational techniques and algorithms for analyzing and mining patterns in large-scale datasets. Techniques studied address data analysis issues related to data volume (scalable and distributed analysis), data velocity (high-speed data streams), data variety (complex, heterogeneous, or unstructured data), and data veracity (data uncertainty). Techniques include mining and machine learning techniques for complex data types, and scale-up and scale-out strategies that leverage big data infrastructures. Real-world applications using these techniques, for instance social media analysis and scientific data mining, are selectively discussed. Students are expected to engage in hands-on projects using one or more of these technologies. Prerequisites: A beginning course in databases and a beginning course in data mining, or equivalent knowledge, and programming experience.

CS 598. Directed Research

CS 599. Master's Thesis

CS 699. Ph.D. Dissertation

Computer Security

Program of Study

A specialization in computer security is available within the master's degree program of the Computer Science (CS) Department.

Students enrolled in this specialization will receive the master of science degree in computer science, with a notation on their transcript "Specialization in Computer Security." The program is focused on preparing students for both industrial positions and Ph.D. study related to computer security.

WPI's cyber-security programs place the science and engineering of security within the broader holistic frameworks of institutions and society. The specialization in Computer Science prepares students to approach technical computer security problems in the context of users and organizations. The M.S. specialization in computer security strives to produce students who

- can assess which security-related threats to address in a computing problem
- understand technical security vulnerabilities and technologies at least two different abstraction levels within computing systems
- appreciate behavioral and human factors in creating feasible security systems

Admission Requirements

The program is conducted at an advanced technical level and requires, in addition to the WPI admissions requirements, a solid background in computer science (CS). Normally a B.S. degree in CS is expected; however, applicants with comparable backgrounds, together with expertise gained through work experience, will also be considered. Interested students should apply to the CS master's degree program. Admission decisions are made by the CS department.

Degree Requirements

33 credits

The Computer Security specialization has both coursework-only and thesis options. The program distribution requirements are as follows:

- Security Core: 6 credits
- Security Electives: 6 credits for the coursework option, or 3 credits for the thesis option. At least one elective course must emphasize Behavioral Dimensions of security.
- Business/Management: 3 credits
- Computer Science Bins: 12 credits
- Either 6 credits of general CS electives (coursework option) or 9 credits of M.S. thesis (thesis option)

The following courses satisfy each requirement:

Security Core: Courses covering two of software, systems/networks, and wireless/internet level security. Current applicable courses are:

- CS 557 (Software Security Design and Analysis)
- CS 558 (Network Security)
- ECE 579W (Wireless and Internet Security)

Students with B.S./M.S. credit for CS 4401 (Software Security Engineering) or CS 4404 (Tools and Techniques in Computer Network Security) may apply at most one of these courses towards the security core requirement for the M.S. specialization.

Security Electives: Includes all security-related courses offered in Computer Science and Electrical and Computer Engineering. Up to three credits from thesis work on a security-related topic may count towards this requirement, with the approval of the specialization director. Current applicable courses are the security core courses as well as:

- CS 571 (Case Studies in Computer Security) [satisfies Behavioral Dimensions requirement]
- CS 578 (Cryptography)
- ECE 673 (Advanced Cryptography)
- CS 564 (Advanced Topics in Computer Security)
- Special topics courses with the approval of the specialization director

At least one course counted towards security electives must provide significant coverage of behavioral dimensions of cyber security. Permanent course offerings that satisfy the behavioral dimensions requirement are designated as such in their catalog descriptions. The instructors of topics courses (CS 525 and CS 5XX) and independent study courses may designate particular offerings as satisfying the behavioral requirement with the approval of the Specialization Director.

Business/Management: Courses covering business or management issues that bear on security concerns. Current applicable courses are:

- MIS 582 (Information Security Management)
- OIE 541 (Operations Risk Management)

Computer Science Bins: Courses as required to satisfy the breadth requirements ("bins") for the CS M.S. degree. Details appear in the CS M.S. degree requirements.

Electives: Any courses allowable within the requirements for CS M.S. degrees, including thesis credits.

Thesis Approval: If a student applies thesis credits towards a degree bearing the computer security specialization, his or her thesis topic must be approved as security-related by one of the core specialization faculty. Theses need not be advised by core specialization faculty; in such cases, the reader should be one of the core specialization faculty.

Important Note

Since the security specialization is within the master's programs of the Computer Science Department, students in this specialization must also satisfy all requirements of the computer science master's program. There is a limit to the number of courses outside of Computer Science that students may apply towards their Computer Science master's degree.

Faculty

E. A. Rundensteiner, Professor, Computer Science Department and Program Director, Data Science. Ph.D., University of California, Irvine, 1992. Big data processing, big data analytics, visual data discovery, stream and pattern mining, large scale data infrastructures.

M. Eltabakh, Associate Professor, Computer Science Department. Ph.D., Purdue University, 2010. Database management systems and information management, query processing and optimization, indexing techniques, scientific data management, and big data analytics.

F. Emdad, Associate Teaching Professor, Data Science Program. Ph.D., Colorado State University, 2007. Business analytics, computational and applied mathematics.

L. Harrison, Assistant Professor, Computer Science Department. Ph.D., University of North Carolina, 2013. Situational awareness, visual analytics, visualization.

X. Kong, Assistant Professor, Computer Science Department, Ph.D., University of Illinois, 2014. Data mining and big data analysis, with emphasis on addressing the data variety issues in biomedical research and social computing, and healthcare analytics.

K. Lee, Assistant Professor, Computer Science Department, Ph.D., Texas A&M University, 2013. Big data analytics and mining, social computing, and cybersecurity over large-scale networked information systems such as the Web, social media and crowd-based systems.

Y. Li, Assistant Professor, Computer Science Department, Ph.D., University of Minnesota, 2013. Ph.D., BUPT, Beijing, China, 2009. Big data from complex networks, large-scale network data measurements, online social behavior modeling, spectal graph theory.

E. T. Loiacono, Professor, Management Information Systems at the Robert A. Foisie School of Business. Ph.D., University of Georgia, 2000. Human computer interaction, affective computing, intersection of technology and people.

C. Ngan, Assistant Teaching Professor, Data Science, Ph.D., George Mason University, 2013. Time Series Analysis, Decision Guidance and Support Systems.

R. C. Paffenroth, Associate Professor, Mathematical Sciences Department, Ph.D., University of Maryland, 1999. Large scale data analytics, statistical machine learning, compressed sensing, network analysis.

J. D. Petruccelli, Professor, Mathematical Sciences Department. Ph.D., Purdue University, 1978. Statistics, time series analysis and statistics education.

C. Ruiz, Associate Professor, Computer Science Department. Ph.D., University of Maryland, 1996. Data mining, machine learning, artificial intelligence, genomics, clinical medicine.

D. M. Strong, Professor, Robert A. Foisie School of Business. Ph.D., Carnegie Mellon University, 1988. Healthcare and business data analytics, computing applications in organizations.

A. C. Trapp, Associate Professor, Robert A. Foisie School of Business. Ph.D., University of Pittsburgh, 2011. Mathematical modeling and optimization applied to social justice: humanitarian operations, inequality; health: healthcare, biomedicine; analytics: data mining; and environment: energy, sustainability.

J. Zou, Assistant Professor, Mathematical Sciences Department. Ph.D., University of Connecticut, 2009. Financial time series and spatial statistics with applications to epidemiology, public health and climate change.

Affiliated Faculty

E. O. Agu, Associate Professor, Computer Science Department. Ph.D., University of Massachusetts, 2001. Computer graphics, mobile computing, and wireless networks.

I. Arroyo, Assistant Professor, Social Science and Policy Studies. D.Ed., University of Massachusetts, 2003. Learning with novel technologies, multimedia learning, intelligent tutoring systems, personalized learning systems

J. Beck, Associate Professor, Computer Science Department. Ph.D., University of Massachusetts, 2001. Educational data mining.

M. Y. Blais, Associate Teaching Professor, Mathematical Sciences. Ph.D., Cornell University, 2006. Liquidity modeling, volatility derivatives, leverage.

D. Brown, III, Associate Professor, Department of Electrical and Computer Engineering. Ph.D., Cornell University, 2000. Communication systems and networking, signal processing, information theory.

L. Capogna, Department Head, Professor, Mathematical Sciences. Ph.D., University of Purdue, 1996. Partial differential equations, calculus of variations and analytic aspects of quasiconformal mappings, sub-Riemannian geometry, minimal surfaces and mean curvature flow.

S. Djamasbi, Associate Professor, Robert A. Foisie School of Business. Ph.D., University of Hawaii, 2004. Management information systems.

J. Doyle, Associate Professor, Social Science and Policy Studies. Ph.D., University of Colorado-Boulder, 1991. Mental models of complex systems, environmental cognition and behavior.

T. Eisenbarth, Associate Professor, Department of Electrical and Computer Engineering. Ph.D., Ruhr-Universiat Bochum, Bochum, Germany, 2009. Embedded system security, side channel analysis, physical attacks and their prevention.

M. Elmes, Professor, Robert A. Foisie School of Business. Ph.D., Syracuse University, 1998. Interpersonal and group dynamics in complex organizations, leading change, leadership ethics.

B. Faber, Professor, Humanities & Arts Department. Ph.D., English University of Utah, 1998. Organizations and change, health care operations and data-intensive methods for understanding health systems and medical practices.

A. Hall-Phillips, Associate Professor, Robert A. Foisie School of Business. Ph.D., Purdue University, 2011. Consumer behavior, business-to-business marketing, small business.

N. T. Heffernan, Professor, Computer Science Department and Co-Director Learning Sciences and Technologies. Ph.D., Carnegie Mellon University, 2001. Educational data mining, intelligent tutoring systems.

M. Hofri, Professor, Computer Science Department. D.Sc., Israel Institute of Technology, Haifa, Israel, 1972. Analysis of algorithms under probabilistic assumptions.

X. Huang, Professor, Department of Electrical and Computer Engineering. Ph.D., Virginia Tech, 2001. Reconfigurable computing, ubiquitous computing and RFID.

M. Humi, Professor, Mathematical Sciences. Ph.D., Weizmann Institute of Science, Rehovot, Israel, 1969. Development and application of mathematical methods to atmospheric research and satellites orbits.

S. Johnson, Professor, Robert A. Foisie School of Business. Ph.D., Cornell University, 1989. Healthcare delivery processes, EHR systems, process analysis and demand.

C. Kasouf, Associate Professor, Robert A. Foisie School of Business. Ph.D., Syracuse University, 1991. Buyer-seller relationships in the supply chain, cognitive factors affecting opportunity recognition.

R. Konrad, Assistant Professor, Robert A. Foisie School of Business. Ph.D., Purdue University, 2009. Decision-analytic modeling, discrete event stochastic simulation-based optimization.

L. Lai, Associate Professor, Department of Electrical and Computer Engineering. Ph.D., Ohio State University, 2007. Wireless network security, information theory, stochastic signal processing

Y. Massoud, Department Head, Professor, Department of Electrical and Computer Engineering. Ph.D., Massachusetts Institute of Technology, 1999. Embedded systems, signal processing, nanotechnology, biotechnology.

F. Miller, Associate Professor, Robert A. Foisie School of Business. Ph.D., Michigan State University, The Eli Broad School of Management, 2007. Accounting, psychology and economics interact.

S. D. Olson, Associate Professor, Mathematical Sciences. Ph.D., North Carolina State University, 2008. Mathematical biology, chemical signaling, mechanics, and hydrodynamics.

E. Ottmar, Assistant Professor, Social Sciences and Policy Study. Ph.D., University of Virginia, 2011. Theories in developmental, educational, and cognitive psychology, and mathematics and teacher education.

M. Radzicki, Associate Professor, Social Science and Policy Studies. Ph.D., University of Notre Dame, 1985. System dynamics modeling, agent-based modeling, predictive analytics.

E. Ryder, Associate Professor, Biology and Biotechnology. Ph.D., Harvard University, 1993. Developmental neurobiology, genetics, bioinformatics, computational biology.

M. Sarkis, Professor, Mathematical Sciences. Ph.D., New York University, 1994. Numerical analysis, finite element methods

G. Sarkozy, Professor, Computer Science Department. Ph.D., Rutgers University, 1994. Graph theory, discrete mathematics, and theoretical computer science.

S. Sturm, Assistant Professor, Mathematical Sciences. Ph.D., Technical University of Berlin, Germany, 2010. Financial mathematics and engineering.

B. Sunar, Associate Professor, Department of Electrical and Computer Engineering. Ph.D., Oregon State University, 1998. Cryptography, network security, high performance computing

D. Tang, Professor, Mathematical Sciences. Ph.D., University of Wisconsin-Madison, 1988. Computational biomathematics, biology and bioengineering.

S. Taylor, Professor, Robert A. Foisie School of Business. Ph.D., Boston College, 2000. Organizational aesthetics, reflective practice, first person research, authentic leadership.

B. Tulu, Associate Professor, Robert A. Foisie School of Business. Ph.D., Claremont Graduate University, 2006. Design and development health information technologies.

B. Vernescu, Professor, Mathematical Sciences. Ph.D., Institute of Mathematics, Bucharest, Romania, 1989. Partial differential equations, homogenization, calculus of variation.

H. Walker, Professor, Mathematical Sciences. Ph.D., New York University, 1970. Computational mathematics, numerical methods for systems of linear and nonlinear equations.

J. Wang, Assistant Professor, Robert A. Foisie School of Business. Ph.D., Lehigh University, 2009. Health economics, corporate governance, applied micro-econometrics.

S. L. Weekes, Professor, Mathematical Sciences. Ph.D., University of Michigan, 1995. Numerical methods, mathematical modeling, dynamic materials.

E. V. Wilson, Associate Professor, Robert A. Foisie School of Business. Ph.D., University of Colorado-Boulder, 1995. E-health, computer mediated communications.

Z. Wu, Associate Professor, Mathematical Sciences. Ph.D., Yale University, 2009. Big data statistical analytics, bioinformatics.

A. Zeng, Assistant Dean, Professor, Robert A. Foisie School of Business. Ph.D., Pennsylvania State University, 1996. Risk and disruption management strategies and tactics in supply chains, global supply chain supply.

J. Zhu, Professor, Robert A. Foisie School of Business. Ph.D., University of Massachusetts, 1998. Performance evaluation and benchmarking, sustainable design and performance.

Faculty Research

Our faculty work in many areas related to Data Science, including in:

- Big data and high performance analytics
- Bioinformatics and genomic data bases
- Business intelligence and predictive analytics
- Cybersecurity analytics
- Cryptography and data security
- Educational data mining

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- Financial decision making
- Healthcare data analytics
- Internet big data analysis
- Large-scale data management and infrastructures
- Machine learning, data mining & knowledge discovery
- Signal processing and information theory
- Social media analytics
- Statistical learning
- Visual and numerical analysis of large data sets

Program of Study

The WPI Data Science (DS) program offers graduate studies toward an M.S., B.S./M.S. and Ph.D. Degree as well as a Certificate in Data Science. This Data Science program educates professionals, Data Scientists, with interdisciplinary skills in analytics, computing, statistics, and business intelligence. Key skills include the ability to recognize problems that can be solved with data analytics, apply the appropriate technologies on a given data problem, and communicate those solutions effectively to relevant stakeholders. Our faculty, together with our industrial partners, provide students with the resources and opportunities to engage in practical, purpose-driven projects, formal course work, and mentored interdisciplinary research work. This Data Science program requires advanced, in-depth course work in business, innovation, data analytics, computing, and statistical foundations. The program is designed to provide focused study in an area of interest to the student, ranging from general data analytics, computing, mathematical analytics, and business analytics, to specialized concentrations in financial analytics, healthcare analytics, biomedical analytics, analytics for sustainability, and learning sciences, among others. Due to their increased interdisciplinary perspective, our graduates will have a clear competitive advantage over professionals who are trained in a single discipline, such as business administration, statistics, or computer science, and who are seeking to work in the data analytic industry. As such, they will be poised to successfully become leaders in Data Science, helping to formalize and realize its vision.

The graduate degree program in Data Science is designed to produce the future generation of data scientists who are proficient in their ability to:

- Assess the suitability of, apply, and advance state-of-art data analytics tools and methods from data analysis, statistics, data mining, data management, computational thinking, big data algorithms, and visualization to bring about transformative solutions to important real-world problems across a number of domains.
- Bring to bear their integrative, interdisciplinary knowledge and skills in the core disciplines central to Data Science (Computing, Statistics, and Business) to understand and then to explain analytics results and their applicability and validity to those responsible for solving real-world problems.
- Serve as visionary leaders and project managers in data analytics, with the technical, and professional knowledge and skills needed for the current and future career demands of data scientists working on impactful projects.

Admissions Requirements

Students applying to the graduate degree program in Data Science (DS) are expected to have a bachelor's degree with a strong quantitative and computational background including coursework in programming, data structures, algorithms, univariate and multivariate calculus, linear algebra and introductory statistics. Students with a bachelor's degrees in computer science, mathematics, business, engineering and quantitative sciences would typically qualify if they meet the above background requirements. A strong applicant who is missing background coursework may be admitted with the expectation that he or she will take and pass one or more undergraduate courses in this area of deficiency either during the summer prior to admission or within the first semester after admission. The determination of what course or courses will satisfy this provision will be made by the DS Program Review Board. Students applying to the Certificate in Data Science are expected to meet the same qualifications described above.

Degree Requirements for the M.S. Degree

Students pursuing the M.S. degree in Data Science must complete a minimum of 33 credits of relevant work at the graduate level. These 33 credits must include the core coursework requirements in Data Science (see below) and either a 3-credit Graduate Qualifying Project (GQP) or a 9-credit M.S. thesis. These M.S. degree requirements have been designed to provide a comprehensive yet flexible program to students who are pursuing an M.S. degree exclusively and also students who are pursuing a combined B.S./M.S. degree.

Upon acceptance to the M.S. program, students will be assigned an academic advisor who will work with the student to correctly prepare a Plan of Study. This Plan of Study must then be approved by the Data Science Program Review Board.

The Data Science M.S. Degree (GQP Project-based)

Graduate Qualifying Project
(3 credits)

Concentration and Electives
(15 credits)

- Mathematical Analytics (3 credits)
- Data Access & Management (3 credits)
- Data Analytics & Mining (3 credits)
- Business Intelligence & Case Studies (3 credits)

Introduction to Data Science
(3 credits)

The Data Science M.S. Degree (M.S. Thesis based)

M.S. Thesis
(9 credits)

Concentration and Electives
(9 credits)

- Mathematical Analytics (3 credits)
- Data Access & Management (3 credits)
- Data Analytics & Mining (3 credits)
- Business Intelligence & Case Studies (3 credits)

Introduction to Data Science
(3 credits)

Core Data Science Coursework Requirement (15 credits)

Students in the M.S. program must take both courses in the Integrative Data Science category and one (1) course from each of the other core Data Science categories listed below:

Integrative Data Science (required):

DS 501. Introduction to Data Science

Mathematical Analytics (Select one):

*MA 543/DS 502. Statistical Methods for Data Science

*MA 542. Regression Analysis

MA 554. Applied Multivariate Analysis

Data Access and Management (Select one):

*CS 542. Database Management Systems

*MIS 571. Database Applications Development

CS 561. Advanced Topics in Database Systems

CS 585/DS 503. Big Data Management

Data Analytics and Mining (Select one):

*CS 548. Knowledge Discovery and Data Mining

CS 539. Machine Learning

CS 586/DS 504. Big Data Analytics

Business Intelligence and Case Studies (Select one):

*MIS 584. Business Intelligence

MKT 568. Data Mining Business Applications

If a student does not have prior background in a particular core category, then it is advised that the student take the course with an asterisk * in the title within that category. If two or more courses have an asterisk *, then the student may select either of these courses based on their personal interest and background. Students *must* take at least 1 course in each of these core areas, but are encouraged to take several. Additional courses taken in a core category will count as electives and/or concentration courses as described below.

Graduate Qualifying Project GQP or M.S. Thesis

A student in the M.S. program must complete one of the following two options:

- **3-credit Graduate Qualifying Project.** (DS 598) This project is most commonly done in teams, and will provide a capstone experience in applying data science skills to a real-world problem. It will be carried out in cooperation with a sponsor or an industrial partner, and must be approved and overseen by a faculty member affiliated with the Data Science Program. A student that follows this practice-oriented project option must gain sufficient Data Science depth by selecting at least 2 courses beyond the required Data Science *core courses* from among the electives below within the *same* area of concentration.
- **9-credit Master's Thesis.** (DS 599) A thesis in the Data Science Program consists of a research or development project worth a *minimum* of 9 graduate credit hours. Students interested in research, and in particular those who are considering a Ph.D. in a related area, are encouraged to select the M.S. thesis option. Any affiliated DS faculty may serve as the thesis advisor. If the advisor is not a tenure-track faculty at WPI, then a DS affiliated tenure-track faculty member must serve as the thesis co-advisor. A thesis proposal must be approved by both the DS Program Review Board *and* the student's advisor before the student can register for more than three thesis credits. The student must then satisfactorily complete a written thesis and present the results to the DS faculty in a public presentation.

Electives and Areas of Concentration (9-15 credits)

A student seeking an M.S. in Data Science program must take course work from the Program electives listed below in order to satisfy the remainder of the 33 credit requirement. An elective may be any of these graduate-level courses, with the restriction that *no more than 16 credits of the 33-credit Data Science degree program may be courses offered by the School of Business.*

While the core areas ensure that students have adequate coverage of essential Data Science knowledge and skills, the wide variety of electives enable students to tailor their Data Science degree program to domain and technique areas of personal interest. Students are expected to select elective course work to produce a consistent program of study. While the core coursework requirements provide the needed breadth in Data Science core categories, students will gain depth in one or several concentrations by choosing appropriate electives from the list of pre-approved courses relevant to data science.

Other courses beyond the pre-approved Program electives may be chosen as electives, but only with *prior approval* by the DS Program Review Board, and if consistent with the student's Plan of Study. For example, students might choose to concentrate their data science expertise on areas of physics, engineering, or sciences, not captured in the electives below. Independent study and directed research courses also require *prior approval* by the DS Program Review Board.

List of Program Elective Courses:

Relevant Business Graduate Courses (a maximum of 16 graduate credits of School of Business coursework may count toward the M.S. in Data Science):

ACC 503. Financial Intelligence for Strategic Decision-Making

BUS 500. Business Law, Ethics and Social Responsibility

FIN 500. Financial Information and Management

FIN 501. Economics for Managers

MIS 500. Innovating with Information Systems

MIS 571. Database Applications Development

MIS 573. Systems Design and Development

MIS 576. Project Management

MIS 581. Information Technology Policy and Strategy

MIS 583. User Experience Applications

MIS 584. Business Intelligence

MKT 568. Data Mining Business Applications

OBC 500. Group and Interpersonal Dynamics in Complex Organizations

OBC 501. Interpersonal and Leadership Skills

OIE 500. Analyzing and Designing Operations to Create Value

OIE 541. Operations Risk Management

OIE 544. Supply Chain Analysis and Design

OIE 552. Modeling and Optimizing Processes

OIE 598. Optimization Methods for Business Analytics

Relevant Computer Science Graduate Courses:

CS 5084. Introduction to Algorithms: Design and Analysis

CS 504. Analysis of Computations and Systems

CS 509. Design of Software Systems

CS 534. Artificial Intelligence

CS 539. Machine Learning

CS 542. Database Management Systems

CS 561. Advanced Topics in Database Systems

CS 548. Knowledge Discovery and Data Mining

CS 584. Algorithms: Design and Analysis

CS 585/DS 503. Big Data Management

CS 586/DS 504. Big Data Analytics

CS 573. Data Visualization

CS 528. Mobile and Ubiquitous Computing

CS 525. Topics in Computer Science (with prior approval of the Program Review Committee to determine relevancy)

CS 536. Programming Language Design

CS 545. Digital Image Processing

CS 546. Human-Computer Interaction

CS 549. Computer Vision

Note: Students may not receive credit for both CS 5084 and CS 584

Relevant Mathematical Sciences Graduate Courses:

MA 543/DS 502. Statistical Methods for Data Science

MA 542. Regression Analysis

MA 554. Applied Multivariate Analysis

MA 552. Distribution-Free and Robust Statistical Methods

MA 550. Time Series Analysis

MA 529. Stochastic Processes

MA 511. Applied Statistics for Engineers and Scientists

MA 540. Probability and Mathematical Statistics I

MA 541. Probability and Mathematical Statistics II

MA 546. Design and Analysis of Experiments

MA 547. Design and Analysis of Observational and Sampling Studies

MA 549. Analysis of Lifetime Data

MA 556. Applied Bayesian Statistics

Relevant Learning Sciences and Technology Program Graduate Courses:

CS 566. Graphical Models For Reasoning Under Uncertainty

CS 565. User Modeling

CS 567. Empirical Methods For Human-Centered Computing

PSY 505. Advanced Methods and Analysis for the Learning and Social Sciences

Relevant Bioinformatics and Computational Biology Program Courses:

BCB 501. Bioinformatics

BCB 502/CS 582. Biovisualization

BCB 503/CS 583. Biological and Biomedical Database Mining

BCB 504/MA 584. Statistical Methods in Genetics and Bioinformatics

Relevant Biomedical Engineering Courses:

BME 595. Special Topics: Machine Learning for Biomedical Informatics

Relevant Electrical and Computer Engineering Department Courses:

ECE 502. Analysis of Probabilistic Signals And Systems

ECE 503. Digital Signal Processing

ECE 504. Analysis of Deterministic Signals And Systems

ECE 578/ CS 578. Cryptography and Data Security

ECE 630. Advanced Topics in Signal Processing

ECE 673. Advanced Cryptography

ECE 5311. Information Theory and Coding

Other Relevant Graduate Courses and Concentration Areas:

Beyond courses in the three core disciplines of computer science, business, and statistics, relevant graduate courses in other potential areas of concentration, such as Finance, Manufacturing, Healthcare, National Security, Engineering, Fraud Detection, Science, Smart Grid Management, Sustainability and the like, may be added in the future to the above list of pre-approved Program electives.

Specializations of the Data Science Degree:

Specializations of the Data Science degree in targeted areas of high societal impact ranging from Health Care to National Security may be designed in the future. We expect these specializations to naturally fit into the flexible structure of the Data Science degree framework.

For the B.S./M.S.

The requirements for the proposed M.S. in Data Science are structured so that undergraduate student would be able to pursue a five-year Bachelors/Masters program, in which the Bachelors degree is awarded in any major offered at WPI and the Masters degree is awarded in Data Science. Students enrolled in the B.S./M.S. program must satisfy all the program requirements of their respective B.S. degree *and* all the program requirements of the M.S. degree in Data Science. WPI allows the double counting of up to 12 credits for students pursuing a 5-year Bachelors-Masters program. This overlap can be achieved through the following mechanisms. They may double-count courses towards both their undergraduate and graduate degrees whose credit hours total no more than *40 percent of the 33 credit hours required for the M.S. degree in Data Science*, and that meet all other requirements for each degree. These courses can include graduate courses as well as certain undergraduate 4000-level course as long as the undergraduate course is acceptable in place of a corresponding graduate course that satisfies a Data Science M.S. requirement. See the individual departmental entries in this catalog for listings of such undergraduate and graduate courses pairs. Students must consult their faculty advisor and the

graduate catalog as individual departments have restrictions on which undergraduate courses may be taken for graduate credit, and on which pairs of undergraduate and graduate courses *cannot both be taken for credit*. Students must register for B.S./M.S. credit prior to taking the courses, as faculty may assign extra work for those taking a 4000-level course as part of both degrees.

In consultation with the academic advisor, the student prepares a Plan of Study outlining the selections chosen to satisfy the B.S./M.S. degree requirements, including the courses that will be double-counted. This Plan of Study must then be approved by the DS Program Review Board.

For the Graduate Certificate

The certificate program in Data Science prepares students to harness, analyze and interpret data in real-word applications. The Certificate Program in Data Science corresponds to the study of 18 credits of graduate work composed of *one* course taken from each of the 5 core categories of Data Science coursework, with the sixth course being an elective in an area of interest or concentration. A Graduate Certificate is granted after completion of this six-course program of study. These courses may be subsequently applied to a degree program at WPI, including the M.S. degree in Data Science, providing the courses meet the requirements of that degree program.

Students who have completed or are currently enrolled in a graduate degree at WPI (other than Data Science) can double count graduate credits from their graduate degree to meet up to 1/3 of the graduate credits for a (subsequent) Graduate Certificate in Data Science.

We anticipate that other certificates in Data Science in specific areas of concentration may be created in the future.

For the Ph.D.

Students are advised to contact the program for detailed rules, as there are program guidelines, in addition to the university's requirements, for the Ph.D. degree.

Upon admission, the student is assigned an academic advisor and together they design a Plan of Study during the first semester of the student's Ph.D. program. A Ph.D. student without a prior M.S. degree is required to take the M.S. thesis Option to engage in research early on.

The student must satisfy the Ph.D. Qualification Requirement, which include the core breadth and core depth competency requirements. The Core breadth competency includes at least one course in each of the core Data Science areas, while the later implies that the student must take at least two courses in two of these core areas. Only courses in which the student has obtained an A or a B grade can be used to satisfy these two competency requirements; with 4 of these 7 courses having to be an A letter grade.

In addition the Ph.D. Qualification requirement also includes the Qualifying Examination. These qualification requirements are described in the Graduate Regulations on the Data Science program website http://wpi.edu/academics/datascience/graduate-program.html.

Upon successful completion of the Ph.D. qualifying requirement, the student becomes a Data Science Ph.D. candidate. The student's Dissertation Committee must be formed within the first year of candidacy. With approval from the Data Science Steering Committee, the student selects a research advisor. Also with approval from the Data Science Steering Committee, the student and research advisor select three additional members, at least one of whom must be from a core data science department different than that of the research advisor and at least one must be from outside of WPI. The Dissertation Committee will be responsible for approving the dissertation proposal and the final dissertation manuscript.

The Ph.D. degree requirements consist of a coursework component and a research component, which together must total at least 60 credit hours beyond the master's degree requirement. The coursework component consists of at least 30 coursework credits, as specified on the Data Science program website http://wpi.edu/academics/datascience/graduate-program.html.

The student may also enroll for research credits, but is only allowed up to 18 research credits prior to the acceptance of the written dissertation proposal by her Dissertation Committee. With approval of the Dissertation Committee, the student applies for and takes the dissertation proposal examination, usually within one year of the Ph.D. candidacy.

The Ph.D. research component consists of at least 30 credits (including any research credits earned prior to the acceptance of the dissertation proposal and excluding any research credits applied toward a master's degree) leading to a dissertation and a public defense, which must be approved by the student's Dissertation Committee.

Affiliated Departments and Programs

This is a joint program administered by the Computer Science Department, Mathematical Sciences Department, and the Robert A. Foisie School of Business. Closely affiliated departments also include Social Science and Policy Studies Department, Learning Sciences and Technologies Program, Bioinformatics and Computational Biology Program, and the Electrical and Computer Engineering Department. Data Science faculty are comprised of faculty interested in Data Science graduate education and research and who hold advanced degrees.

Industrial Relationships

In collaboration with WPI's Corporate and Professional Education, the Data Science faculty work with industrial, government and academic partners who serve on an Advisory Board to help shape the WPI Data Science program and its offerings to assure its continued relevancy. In addition, these Advisory Board members provide input on industrial hiring needs, offer projects and internships to Data Science students, and serve as employers of our graduates.

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Course Descriptions

All courses are 3 graduate credits unless otherwise stated.

DS 501. Introduction to Data Science

Introduction to Data Science provides an overview of Data Science, covering a broad selection of key challenges in and methodologies for working with big data. Topics to be covered include data collection, integration, management, modeling, analysis, visualization, prediction and informed decision making, as well as data security and data privacy. This introductory course is integrative across the core disciplines of Data Science, including databases, data warehousing, statistics, data mining, data visualization, high performance computing, cloud computing, and business intelligence. Professional skills, such as communication, presentation, and storytelling with data, will be fostered. Students will acquire a working knowledge of data science through hands-on projects and case studies in a variety of business, engineering, social sciences, or life sciences domains. Issues of ethics, leadership, and teamwork are highlighted. Prerequisites: None beyond meeting the Data Science admission criteria.

DS 502/MA 543. Statistical Methods for Data Science

Statistical Methods for Data Science surveys the statistical methods most useful in data science applications. Topics covered include predictive modeling methods, including multiple linear regression, and time series, data dimension reduction, discrimination and classification methods, clustering methods, and committee methods. Students will implement these methods using statistical software. Prerequisites: Statistics at the level of MA 2611 and MA 2612 and linear algebra at the level of MA 2071.

DS 503/CS 585. Big Data Management

Big Data Management deals with emerging applications in science and engineering disciplines that generate and collect data at unprecedented speed, scale, and complexity that need to be managed and analyzed efficiently. This course introduces the latest techniques and infrastructures developed for big data management including parallel and distributed database systems, map-reduce infrastructures, scalable platforms for complex data types, stream processing systems, and cloud-based computing. Query processing, optimization, access methods, storage layouts, and energy management techniques developed on these infrastructures will be covered. Students are expected to engage in hands-on projects using one or more of these technologies. Prerequisites: A beginning course in databases at the level of CS 4432 or equivalent knowledge, and programming experience.

DS 504/CS 586. Big Data Analytics

Big Data Analytics addresses the obstacle that innovation and discoveries are no longer hindered by the ability to collect data, but by the ability to summarize, analyze, and discover knowledge from the collected data in a scalable fashion. This course covers computational techniques and algorithms for analyzing and mining patterns in large-scale datasets. Techniques studied address data analysis issues related to data volume (scalable and distributed analysis), data velocity (high-speed data streams), data variety (complex, heterogeneous, or unstructured data), and data veracity (data uncertainty). Techniques include mining and machine learning techniques for complex data types, and scale-up and scale-out strategies that leverage big data infrastructures. Real-world applications using these techniques, for instance social media analysis and scientific data mining, are selectively discussed. Students are expected to engage in hands-on projects using one or more of these technologies. Prerequisites: A beginning course in databases and a beginning course in data mining, or equivalent knowledge, and programming experience.

DS 594. Data Science Internship

(1 to 3 credits)

The internship is an elective-credit option designed to provide an opportunity to put into practice the principles studied in previous Data Science courses. Internships will be tailored to the specific interests of the student. Each internship must be carried out in cooperation with a sponsoring organization, generally from off campus and must be approved and advised by a core faculty member in the Data Science program. The internship must include proposal, design and documentation phases. Following the internship, the student will report on his or her internship activities in a mode outlined by the supervising faculty member. Students are limited to counting a maximum of 3 internship credits towards their degree requirements for the M.S. degree in Data Science. We expect a full-time graduate student to take on only part-time (20 hours or less of) internship work during the regular academic semester, while a full-time internship of 40 hours per week is appropriate during the summer semester as long as the student does not take a full class load at the same time. Internship credit cannot be used towards a certificate degree in Data Science. The internship may not be completed at the student's current place of employment. Prerequisites: Registration for internship credit requires prior approval and signature by the academic advisor.

DS 595. Special Topics in Data Science

Special Topics in Data Science is course offering that will cover a topic of current interest in detail. This serves as a flexible vehicle to provide a one-time offering of topics of current interest as well as to offer new topics before they are made into a permanent course. Prerequisites: will vary with topic.

DS 596. Independent Study

Independent Study, as the name suggests, is a course that allows a student to study a chosen topic in Data Science under the guidance of a faculty member affiliated with the Data Science program. The student must produce a written report to satisfy the course requirement.

DS 597. Directed Research

Directed Research study, conducted under the guidance of a faculty member affiliated with the Data Science Program, investigates the challenges and techniques central to data science, and aims to develop novel approaches and techniques towards solving these challenges. The student who chooses this course must produce a written report to fulfil the course requirement.

DS 598. Graduate Qualifying Project

The Graduate Qualifying Project, or GQP, is a 3-credit project, typically done in teams that is carried out in cooperation with a sponsor or industrial partner. It will be overseen by a faculty member affiliated with the Data Science Program and will offer integrated theory and practice of Data Science including the utilization of tools and techniques acquired in the Data Science Program. In addition to a written report, this project must be presented in a formal demonstration to the faculty of the Data Science program and sponsors. Professional development skills, such as communication, teamwork, leadership, and collaboration, along with storytelling, will be practiced. Prerequisites: DS 501, completion of at least 24 credits of the DS degree, and consent of the instructor.

DS 599. Master's Thesis in Data Science

The Master's Thesis in Data Science consists of a research and development project worth a minimum of 9 graduate credit hours and is advised by a faculty member affiliated with the Data Science Program. A thesis proposal must be approved by the DS Program Review Board and the student's advisor, before the student can register for more than three thesis credits. The student must satisfactorily complete a written thesis document, and present the results to the DS faculty in a public presentation.

DS 699. Dissertation Research.

Intended for doctoral students admitted to candidacy wishing to obtain research credit toward their dissertations. (Prerequisite: Consent of Dissertation Advisor.)

Electrical and Computer Engineering

www.ece.wpi.edu

Faculty and Research Interests

Y. Massoud, Professor and Department Head; Ph.D., Massachusetts Institute of Technology. Embedded systems, signal processing, nanotechnology, biotechnology.

D. R. Brown, Professor; Ph.D., Cornell University. Wireless communications and networks, cooperative communication systems, synchronization, efficient resource allocation, distributed decision making, game-theoretic analysis of networks, peer-to-peer networks, cognitive radio, software defined radio, computationally efficient signal processing, security in wireless communication systems.

E. A. Clancy, Professor; Ph.D., MIT. Biomedical signal processing and modeling, biomedical instrumentation.

A. Clark, Assistant Professor; Ph.D., University of Washington. Security, control of cyber-physical systems.

D. Cyganski, Professor and Dean of Engineering; Ph.D., Worcester Polytechnic Institute. Precision indoor location systems, sensor systems for first responder safety, radar, sonar, and optical phased arrays for automatic target recognition.

R. J. Duckworth, Associate Professor; Ph.D., Nottingham University. Embedded computer system design, computer architecture, real-time systems, wireless instrumentation, rapid prototyping, logic synthesis, location and tracking systems.

T. Eisenbarth, Associate Professor; Ph.D., Ruhr University Bochum. IT security, with a focus on the security of embedded systems and applied cryptology. Topics of special interest include embedded security design, physical security and side channel cryptanalysis, and efficient implementation of cryptographic algorithms.

A. E. Emanuel, Professor; D.Sc., Israel Institute of Technology. Power quality, power electronics, electromagnetic design, high-voltage technology.

J. Fu, Assistant Professor; Ph.D., University of Delaware. Reactive robotic systems, multi-robot coordination, optimal control of hybrid systems and design of adaptive semi-autonomous systems.

X. Huang, Professor; Ph.D., Virginia Tech. Reconfigurable computing; VLSI and SoC design; parallel processing.

H. Hakim, Associate Professor; Ph.D., Purdue University. Digital signal processing, system engineering.

L. Lai, Associate Professor; Ph.D., Ohio State University. Wireless network security, information theory and statistical signal processing.

F. J. Looft, Professor; Ph.D., University of Michigan. Digital and analog systems, microprocessor and embedded systems, space-flight systems, robots and robotic systems, robot sensors, alternative energy systems, systems engineering capstones and education.

R. Ludwig, Professor; Ph.D., Colorado State University. Design of RF and surface gradient coils for magnetic resonance imaging; computational modeling of micropatch antennas; DC-coupled RF/MW wideband amplified design; nondestructive material evaluation of critical components.

Y. Mahmoud, Assistant Professor; Ph.D., University of Waterloo, Canada. Solar energy conversion, renewable energy integration, power electronics, dispatchability in renewable energy systems, control and operation of micro grids, and smart cities.

S. N. Makarov, Professor; Ph.D., St. Petersburg State University (Russia). Electromagnetic therapeutic devices, antennas, and electromagnetic sensors for human body applications. CAD human body models.

J. A. McNeill, Professor and Associate Department Head; Ph.D., Boston University. Analog IC design; high-speed imaging; mixed-signal circuit characterization.

W. R. Michalson, Professor; Ph.D., Worcester Polytechnic Institute. Navigation and tracking; high-performance embedded computer systems.

J. A. Orr, Professor; Ph.D. University of Illinois at Urbana-Champaign. Digital signal processing and communications as applied to indoor navigation systems and electrical power systems, engineering education.

T. Padir, Visiting Assistant Professor; Ph.D., Purdue University; Modeling and control of robotic systems, kinematics and dynamics of robot manipulators, redundancy resolution and trajectory planning, automated system design, machine vision.

K. Pahlavan, Professor; Ph.D., Worcester Polytechnic Institute. Wireless networks.

P. C. Pedersen, Professor Emeritus and Director of the Denmark Project Center; Ph.D., University of Utah. Ultrasound in telemedicine, ultrasound training systems, 3D imaging and visualization, elastography, automated image analysis, ultrasound based atherosclerotic plaque classification..

B. Sunar, Professor; Ph.D., Oregon State University. Security; cryptography; computer arithmetic; finite fields; high-speed computing.

R. F. Vaz, Associate Professor, Dean of the Interdisciplinary and Global Studies Division, Co-Director of the Bangkok and Limerick Project Centers; Ph.D., Worcester Polytechnic Institute. Technological education reform, internationalization of higher education, project-based education, sustainable design and appropriate technology.

A. M. Wyglinski, Associate Professor; Ph.D., McGill University. Wireless communication systems engineering, vehicular technology, cognitive radio, software-defined radio, autonomous vehicles, wireless spectrum, vehicular security, cyber-physical systems.

Programs of Study

The Electrical and Computer Engineering (ECE) Department offers programs leading to M.Eng., M.S. and Ph.D. degrees in electrical and computer engineering, an M.Eng. degree in power systems engineering (PSE), as well as graduate and advanced certificates. The following general areas of specialization are available to help students structure their graduate courses: biomedical signal processing/instrumentation, communications and signal processing, computer engineering, electromagnetics

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and ultrasonics engineering, electronics and solid state, power engineering, and systems and controls.

The M.S. ECE degree is designed to provide an individual with advanced knowledge in one or more electrical and computer engineering areas via successful completion of at least 21 credits of WPI ECE graduate courses (including M.S. thesis credit), combined with up to 9 credits of coursework from computer science, mathematics, physics and other engineering disciplines.

The M.Eng. ECE and M.Eng. PSE degrees are tailored for individuals seeking an industrial career path. Similar to the M.S. degree, the M.Eng. degree requires the successful completion of at least 21 credits of WPI ECE graduate courses (specific course requirements for the M.S. ECE and M.S. PSE degrees are discussed below). In contrast to the M.S. degree, the M.Eng. degree allows up to 9 credits on non-ECE courses to be chosen as management courses and does not include a thesis option.

Admission Requirements

Master's Program

Students with a B.S. degree in electrical engineering or electrical and computer engineering may submit an application for admission to the Master's program. There are three degree options in the Master's program: An M.S. in Electrical and Computer Engineering, an M.Eng. in Electrical and Computer Engineering, and an M.Eng. in Power Systems Engineering. Admission to the Master's program will be based on a review of the application and associated references.

Applicants without a B.S. degree in electrical engineering or electrical and computer engineering, but who hold a B.S. degree in mathematics, computer engineering, physics or another engineering discipline, may also apply for admission to the Master's program in the Electrical and Computer Engineering Department. If admitted, the applicant will be provided with required courses necessary to reach a background equivalent to the B.S. degree in electrical engineering or electrical and computer engineering, which will depend on the applicant's specific background.

Applicants with the bachelor of technology or the bachelor of engineering technology degree must typically complete about 1-1/2 years of undergraduate study in electrical engineering before they can be admitted to the graduate program. If admitted, the applicant will be provided with required courses necessary to reach a background equivalent to the B.S. degree in electrical engineering or electrical and computer engineering, which will depend on the applicant's specific background.

Ph.D. Program

Students with a Master's degree in electrical and computer engineering may apply for the doctoral program of study. Admission to the Ph.D. program will be based on a review of the application and associated references. Students with a Bachelor of Science degree in electrical and computer engineering may also apply to the Ph.D. program. Students with a strong background in areas other than Electrical and Computer Engineering will also be considered for admission into the Ph.D. program. If admitted (based on review of the application and associated references), the applicant may be approved for direct admission to the Ph.D. program, or to an M.S.-Ph.D.. program sequence. Applicants possessing and M.S. degree in electrical and computer engineering from WPI that have not been directly admitted to the Ph.D. program are still required to submit an application and associated references for consideration, with the exception of GRE scores, TOEFL scores, and the application fee.

Certificate Requirements

The ECE Department offers advanced certificate and graduate certificate programs. Please visit http://www.wpi.edu/academics/ece/certificate-program.html for more details about these certificate programs.

Degree Requirements

There are three degree options within the Master's program in the Electrical and Computer Engineering Department: A Master of Engineering in Electrical and Computer Engineering (M.Eng. ECE), a Master of Science in Electrical and Computer Engineering (M.S. ECE), and a Master of Engineering in Power Systems Engineering (M.Eng. PSE).

Master of Science ECE

Students pursuing the M.S. ECE degree may take either the non-thesis option, which requires 30 graduate credits in course work, independent study, or directed research, or the thesis option, with a total of 30 graduate credits including a 9-credit thesis. In either case, at least 21 of the 30 credits must be graduate level activity (designated 500-, 5000-, or 600-level) in the field of electrical and computer engineering (course prefix ECE) offered by WPI. The remaining credits may be either at the 4000 (maximum of six credits) or the 500 level in computer science (CS), physics (PH), engineering (BME, CHE, CE, ECE, FP, MFE, MTE, ME, RBE, and SYS) and/or mathematics (MA). The complete program must be approved by the student's advisor and the Graduate Program Committee.

Master of Engineering ECE

Students pursuing the M.Eng. ECE degree require 30 graduate credits in course work, independent study, or directed research. There is no thesis option for the M.Eng. ECE degree program. At least 21 of the 30 credits must be graduate level activity (designated 500-, 5000-, or 600-level) in the field of electrical and computer engineering (course prefix ECE) offered by WPI. The remaining credits may be either at the 4000 level (maximum of six credits) or at the graduate level in computer science (CS), physics (PH), engineering (BME, CHE, CE, ECE FP, MFE, MTE, ME, RBE, and SYS), mathematics (MA), and/or from the School of Business (ACC, BUS, ETR, FIN, MIS, MKT, OBC, and OIE). The complete program must be approved by the student's advisor and the Graduate Program Committee.

Master of Engineering PSE

The M.Eng. PSE is primarily delivered to industry professionals at a variety of off-campus locations; students should contact the ECE office staff regarding course availability. Students pursuing the M.Eng. PSE degree require 30 graduate credits in course work, independent study, or directed research. There is no thesis option for the M.Eng. PSE degree program. At least 21 of the 30 credits must be graduate level activity in the field of electrical and computer engineering offered by WPI; of these 21 credits, at least 15 must be in the field of power system engineering (course prefix

ECE with course numbers from 5500 through 5599). The remaining courses may be either at the 4000 level (maximum of six credits) or at the graduate level (designated as 500-, 5000-, or 600-level) in computer science (CS), physics (PH), engineering (BME, CHE, CE, ECE, FP, MFE, MTE, ME, RBE, and SYS), mathematics (MA), and/or from the School of Business (ACC, BUS, ETR, FIN, MIS, MKT, OBC, and OIE).

Program of Study

Each student must submit a program of study for approval by the student's advisor, the ECE Department Graduate Program Committee and the ECE Department Head. To ensure that the Program of Study is acceptable, students should, in consultation with their advisor, submit it to the ECE Department Graduate Secretary prior to the end of the semester following admission into the graduate program. Students must obtain prior approval from the ECE Department Graduate Program Committee for the substitution of courses in other disciplines as part of their academic program.

All full-time students in the Master's degree program (with the exception of B.S./M.S. students as noted below) are required to attend and pass the two graduate seminar courses, ECE 596A (fall semester) and ECE 596B (spring semester). See course listings for details.

Thesis Option

Students pursuing an M.S. ECE degree that are financially supported by the department in the form of teaching assistantship, research assistantship, or fellowship are required to complete a thesis. The thesis option is not available for students pursuing an M.Eng. ECE or M.Eng. PSE degree. M.S. thesis research involves 9 credit hours of work, registered under the designation ECE 599, normally spread over at least one academic year. For students completing the M.S. thesis as part of their degree requirements, a thesis committee will be set up during the first semester of thesis work. This committee will be selected by the student in consultation with the major advisor and will consist of the thesis advisor (who must be a full-time WPI ECE faculty member) and at least two other faculty members whose expertise will aid the student's research program. An oral presentation before the Thesis Committee and a general audience is required. In addition, all WPI thesis regulations must be followed.

Non-Thesis Option

Although the thesis is optional for M.S. ECE students not financially supported by the department, and there is no thesis option available for M.Eng. ECE or M.Eng. PSE students, all M.Eng. and M.S. students are encouraged to include a research component in their graduate program. A directed research project, registered under the designation ECE 598, involves a minimum of 3 credit hours of work under the supervision of a faculty member. The task is limited to a well-defined goal. Note that the Graduate Program committee will not allow credit received under the thesis designation (ECE 599) to be applied toward an M.Eng. ECE degree, M.Eng. PSE degree, or non-thesis M.S. ECE degree.

Transfer Credit

Students may petition to transfer a maximum of 15 graduate semester credits, with a grade of B or better, after they have enrolled in the degree program. This may be made up of a combination of up to 9 credits from the WPI ECE graduate courses taken prior to formal admission and up to 9 credits from other academic institutions. Transfer credit will not be allowed for undergraduate level courses taken at other institutions. In general, transfer credit will not be allowed for any WPI undergraduate courses used to fulfill undergraduate degree requirements; however note that there are exceptions in the case of students enrolled in the B.S./M.S. program.

For the Ph.D.

The degree of doctor of philosophy is conferred on candidates in recognition of high scientific attainments and the ability to carry on original research. The following is a list of requirements for students intending to obtain a Ph.D. in Electrical and Computer Engineering.

Coursework and Residency Requirements

Students must complete 60 or more credits of graduate work beyond the credit required for the Master of Science degree in Electrical and Computer Engineering. Of the 60 credits, at least 30 credits must be research registered under the designation ECE 699. The doctoral student must also establish two minors in fields outside of electrical engineering. Physics, mathematics and/or computer science are usually recommended. Each student selects the minors in consultation with their Research Advisor. At least 6 credits of graduate work is required in each minor area. Courses with an ECE designation which are cross-listed in the course offerings of another department cannot be used toward fulfilling the requirements of a minor area.

All doctoral students are required to attend and pass two offerings of the ECE graduate seminar courses, ECE 596A (fall semester) and ECE 596B (spring semester). These students may either enroll in the same ECE graduate seminar course offered in two different semesters, or enroll in each of the two different ECE graduate seminar courses. Note that enrollment in these two courses is required regardless if the student has already successfully passed these courses and counted them towards the requirements of an M.S. degree or equivalent credit.

Full-time residency at WPI for at least one academic year is required while working toward a Ph.D. degree.

Research Advisor and Committee Selection

The doctoral student is required to select a Research Advisor and their Committee prior to scheduling their Diagnostic Examination. This will usually occur prior to the start of the student's second semester in the graduate program. The Research Advisor and all members of the Committee must hold doctoral degrees. The Research Advisor must be a full-time ECE faculty member. The Committee must consist of at least two faculty members, at least one of which must be an ECE faculty member and at least one of which must be from outside the ECE department or from outside WPI. The Committee is usually selected by the student in consultation with the Research Advisor. All members of the committee must be approved by the Research Advisor.

A completed Research Advisor and Committee Selection form must be filed with the ECE department prior to taking the Diagnostic Exam. A student may change their Research Advisor or members of their Committee by submitting a

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new Research Advisor and Committee Selection form to the Graduate Secretary. Changes to the student's Research Advisor after completion of the diagnostic examination must be approved by the ECE Graduate Program Committee. Changes to the student's Committee after completion of the area examination must be approved by the ECE Graduate Program Committee.

Diagnostic Examination Requirement

The doctoral student is required to complete the diagnostic examination requirement during the first year beyond the M.S. degree (or equivalent number of credits, for students admitted directly to the Ph.D. program) with a grade of Pass. The diagnostic examination is scheduled with the student's Research Advisor and Committee. Prior to scheduling the diagnostic examination, a student must have a completed Research Advisor and Committee Selection form on file in the ECE department.

The diagnostic examination is administered by the student's Research Advisor and at least one member of the Committee. Full participation of the Committee is recommended. At the discretion of the research advisor, additional faculty outside of the student's committee may also participate in the diagnostic examination. The diagnostic examination is intended to be an opportunity to evaluate the student's level of academic preparation and identify any shortcomings in the student's background upon entrance to the Ph.D. program. The format and duration of the diagnostic examination is at the discretion of the student's Research Advisor and Committee. The examination may be written or oral and may include questions to test the general background of the student as well as questions specific to the student's intended area of research.

The Research Advisor and Committee determine the outcome of the diagnostic examination (Pass, Repeat, or Fail) and any required remediation intended to address shortcomings identified in the student's background. A grade of Fail will result in dismissal from the graduate program. A grade of Repeat requires the student to reschedule and retake the diagnostic examination. A grade of Pass is expected to also include a summary of any prescribed remediation including, but not limited to, coursework, reading assignments, and/or independent study. Irrespective of outcome of the examination, a diagnostic examination completion form, signed by the student's Research Advisor and committee, must be filed with the ECE department upon completion of the examination.

Upon successful completion of the Diagnostic Examination, each doctoral student must submit a program of study to the ECE Department Graduate Secretary for approval by the student's research advisor, the ECE Department Graduate Program Committee and the ECE Department Head. The program of study should be completed in consultation with the student's research advisor and should include specific course work designed to address any shortcomings identified in the student's background during the Diagnostic Examination.

Area Examination Requirement

The doctoral student is required to pass the area examination before writing a dissertation. The area examination is intended to be an opportunity for the student's Advisor and Committee members to evaluate the suitability, scope, and novelty of the student's proposed dissertation topic. The format of the area examination is at the discretion of the student's Advisor and Committee but will typically include a presentation by the student describing the current state of their research field, their planned research activities, and the expected contributions of their work.

Students are eligible to take the area examination after they have successfully completed the diagnostic examination and have completed at least three semesters of coursework in the graduate program. All Ph.D. students are required to successfully complete the area examination prior to the completion of their seventh semester in the graduate program. Failure to successfully complete the area examination prior to the end of the student's seventh semester will be considered a failure to make satisfactory academic progress.

The Research Advisor and Committee determine the Pass/Fail outcome of the area examination. A grade of Fail will result in dismissal from the graduate program. Area examination completion forms must be signed by the student's Research Advisor and Committee Members and filed with the ECE department upon completion of the examination.

Dissertation Requirement

All Ph.D. students must complete and orally defend a dissertation prepared under the general supervision of their Research Advisor. The research described in the dissertation must be original and constitute a contribution to knowledge in the major field of the candidate. The Research Advisor and Committee certify the quality and originality of the dissertation research, the satisfactory execution of the dissertation and the preparedness of the defense.

The Graduate Secretary must be notified of a student's defense at least seven days prior to the date of the defense, without exception. A student may not schedule a defense until at least three months after they have completed the area examination.

For the Combined B.S./M.S. Program

A WPI student accepted into the B.S./M.S. program may use 12 credit hours of work for both the B.S. and M.S. degrees. Note that students will not be able to receive an M.Eng. ECE or M.Eng. PSE degree via this particular program. At least 6 credit hours must be from graduate courses (including graduate level independent study and special topics courses), and none may be lower than the 4000-level. No extra work is required in the 4000-level courses. A grade of B or better is required for any course to be counted toward both degrees. A student must define the 12 credit hours at the time of applying to the B.S./M.S. program. Applications will not be considered if they are submitted prior to the second half of the applicant's junior year. Ideally, applications (including recommendations) should be completed by the early part of the last term of the junior year.

At the start of Term A in the senior year, but no later than at the time of application, students are required to submit to the graduate coordinator of the Electrical and Computer Engineering Department a list of proposed courses to be taken as part of the M.S. degree program. A copy of the student's academic transcript (grade report) must be included with the application.

All students in the B.S./M.S. program in Electrical and Computer Engineering who have completed their B.S. degree must register for at least six credits per semester until they complete 30 credits toward their

M.S. degree. If fewer than six credits are required to complete the M.S. degree, then the student must register for at least the number of credits required to complete the degree. If a student double counts a full 12 credits for both the M.S. and B.S. degrees, then the remaining 18 credits must be completed within 3 semesters of graduate work (1.5 years). Students who double count less than 12 credits for both the M.S. and B.S. degree will be allowed an additional semester (2 years) to complete the degree.

All B.S./M.S. students are required to attend and pass one of the graduate seminar courses, either ECE 596A (fall semester) or ECE 596B (spring semester).

Students enrolled in the B.S./M.S. program in Electrical and Computer Engineering may petition for permission to use a single graduate course (3 credits maximum) taken at other institutions to satisfy ECE B.S./M.S. degree requirements. The course must be at the graduate level and the student must have earned a grade of B or better to be considered for transfer credit.

Certificate in Power Systems Engineering

This specialized program raises professional competency levels of protection engineers and focuses solely on the protection and control aspects of the power industry.

This certificate consists of 12-18 credits of graduate coursework.

Electrical and Computer Engineering Research Laboratories/Centers

Analog/Mixed Signal Microelectronics Laboratory

Prof. McNeill

The Analog and Mixed Signal Microelectronics Laboratory focuses on the continuation of research in self-calibrating analog to-digital converter architectures and low-jitter clock generation; funded by NSF, Allegro Microsystems, and Analog Devices. www.wpi.edu/+ECE

Antenna Laboratory

Prof. Makarov

The Antenna Laboratory uses modeling and hardware design of UHF, L-band, and X-band antennas including wearable antennas (low UHF), base station wideband GPS/modernized GPS antennas (L-band), the broadband rib-cage dipoles, and the UHF non-scanning antenna arrays for directed power applications. www.wpi.edu/+ECE

Center for Advanced Integrated Radio Navigation (CAIRN)

Prof. Michalson

The Center for Advanced, Integrated, Radio Navigation (CAIRN) mission is the development of radio systems that integrate communications and navigation functions. Basic research into radio design (analog and digital), wireless ad hoc networking and positioning is performed for both indoor and outdoor radio environments. The laboratory develops, designs, implements, and field-tests a variety of radio and navigation systems. Housed within the laboratory is the Public Safety Integration Center, which focuses on the development and deployment of communications, information, and navigation technologies for public safety applications. Representative projects: Radio systems for indoor positioning, Digital radios for public safety systems, Simulation of wireless ad hoc networks for public safety applications. http://www.wpi.edu/academics/ece/cairn/index.html

Center for Wireless Information Networking Studies (CWINS)

Prof. Pahlavan

The mission of the Center for Wireless Information Network Studies is the analysis of wideband radio propagation for design and performance evaluation of wireless access and localization techniques. The current focus of research is on body area networking and in particular localization of wireless video capsule endoscope inside the small intestine. The past focus of the center were on indoor geolocation and Wi-Fi localization for application in smart devices and robots. The center was established in 1985 as the world's first research center for the design of wireless local area networks. More details on the center are available at www.cwins.wpi.edu.

Collective Intelligence and Bionic Robotics (CIBR) Lab

Prof. Fu (ECE) and Prof. Li (ME)

CIBR lab is a joint lab between ECE faculty Jie Fu and ME faculty Zhi Li, under the Robotics Engineering Program. Our research focus is to bring a joint force between control theory, machine learning and robotics to achieve two major objectives: First, by leveraging learning-based control design, we aim to develop algorithms to achieve provably safe, adaptive and robust performance in autonomous systems in the presence of uncertain and dynamical environment. Second, we aim to build the algorithmic foundation for bionic robotics that facilitates a seamless collaboration between human and robots, with applications to advanced manufacturing, health, and medical robotics.

Embedded Computer Laboratory

Prof. Huang

The mission of the Embedded Computing Lab is to solve important problems of embedded computer systems, including theories, architectures, circuits, and systems. Our current research is focused on ASIC, FPGA and SoC design for signal processing, wireless communications, error correction coding, reconfigurable computing, and computing acceleration. Our research goal is to create new architectures and circuit designs to facilitate high-speed information processing at minimum power consumption. http://computing.wpi.edu/

Information Processing, Networking and Security (IPNS) Lab

Prof. Lai

The main research focus of the IPNS Lab is information theory, stochastic signal processing and their applications in communications, complex networks, security, and other related areas. We are particularly interested in how to extract, process and transmit useful information efficiently, reliably and securely. In the IPNS Lab, we strive to understand the fundamental limits and are also interested in designing practical schemes to approach or achieve these fundamental limits.

Laboratory for Sensory and Physiologic Signal Processing – L(SP)^2

Prof. Clancy

The mission of the Laboratory for Sensory and Physiologic Signal Processing L(SP)2 is to employ signal processing, mathematical modeling, and other electrical and computer engineering skills to study applications involving electromyography (EMG — the electrical activity of skeletal muscle). Researchers are improving the detection and interpretation of EMG for such uses as the control of powered prosthetic limbs, restoration of gait after stroke or traumatic brain injury, musculoskeletal modeling, and clinical/scientific assessment of neurologic function. http://users.wpi.edu/~ted/

Precision Personnel Locator Project and Convergent Technologies Center (CTC)

Prof. Cyganski and Prof. Duckworth

The mission of the Precision Personnel Locator Project is to protect the lives of emergency responders and to enhance their ability to accomplish their missions through research and development of systems for personnel location and tracking, physiological status monitoring, environmental sensing, and command and control. This project brings together diverse technical capabilities from other centers and laboratories at WPI to address important problems for emergency responders, the most critical of which is precise location knowledge for each person. The primary center involved in the current work is the Convergent Technology Center (CTC). The Convergent Technology Center contributes expertise in advanced signal and image processing, information fusion, algorithm design, communication and computer networks. Another important aspect of this work is that, as an academic enterprise, this project involves graduate students as research assistants, and undergraduate students as summer interns. The opportunity for research and development at the state of the art in communications, computation, and positioning, is an unparalleled experience for our students. http://www.wpi.edu/academics/ece/ppl/index.html

Renewable Energy Innovations Laboratory

Prof. Mahmoud

Our lab emphasizes all aspects of innovations in renewable energy systems for the conversion, delivery, and its use in electrical form. Our aim is to contribute in expanding the utilization of renewable energy resources in the world by addressing technical challenges impeding their utilization, including reducing their cost, and improving their overall efficiency, operation, control, integration and reliability. Our objective is also to commercialize and transfer our developed technologies to market. https://www.wpi.edu/people/faculty/yamahmoud

RF-Electronic and Medical Imaging Laboratory

Prof. Ludwig

The RF-Electronics and Medical Imaging Laboratory uses clinical and animal research in such diverse fields as neurology and oncology. The lab has access to high-field and ultra high-field magnetic resonance imaging (MRI) systems for use in functional and anatomical imaging. Major research focuses on visualization of elastic vibrations in the female breast. A novel coil geometry was designed that proved more efficient at generating these strong gradients when compared with conventional coil technology. Research has resulted in the design of special-purpose radio frequency array coil systems for breast cancer diagnosis, bone density determination, and stroke. The lab has successfully tested its single-tuned and dual-tuned prototypes at various sites throughout the U.S. in clinical MRI systems. www.wpi.edu/+ECE

Secure Cyber-Physical Systems Lab

Prof. Clark

Cyber-Physical Systems (CPS) are comprised of tightly integrated cyber (sensing, communication, computation) and physical (actuation) components in applications including transportation, medicine, energy, and housing. The goal of our lab is to develop foundations for CPS with provable guarantees on safety, performance, and security, in the presence of dynamic environments, random faults and failures, and malicious attacks.

Signal Processing and Information Networking Laboratory (SPINLab)

Prof. Brown

SPINLab was established in 2002 to investigate fundamental and applied problems in signal processing, communication systems, and networking. Our current focus is on the development of network carrier synchronization schemes to facilitate distributed beamforming and space-time coded cooperative transmission. We are also working on techniques for optimal resource allocation in multiuser communication systems and the application of game-theoretic tools to analyze selfish behavior in cooperative communication systems. SPINLab offers research opportunities at both the graduate and undergraduate levels. For more details, please see the SPINLab Web page at http://spinlab.wpi.edu.

Vernam Group

Profs. Eisenbarth, Lai, Sunar, Martin (Mathematics), and Venkatasubramanian (CS)

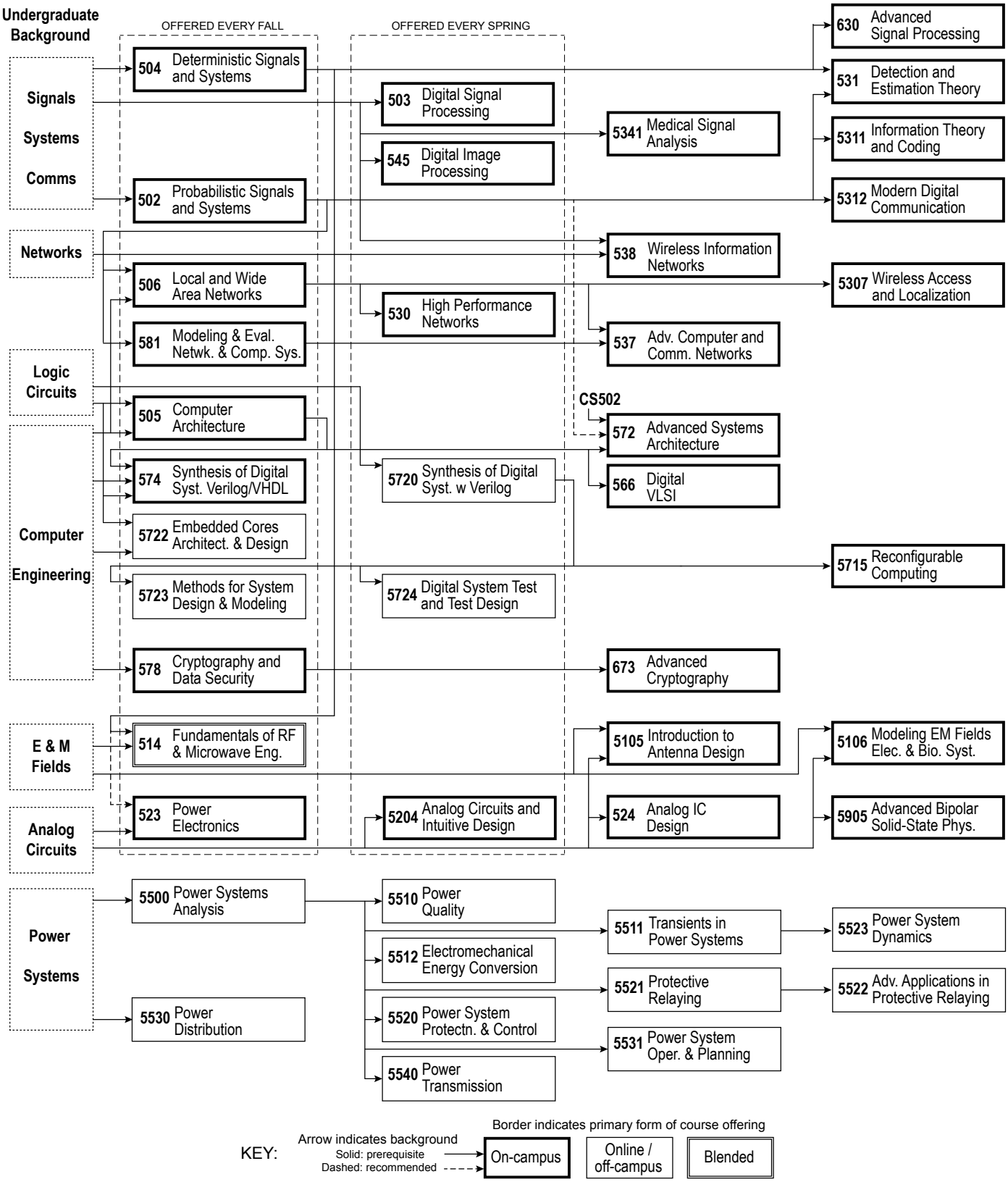
The mission of the Vernam Group is to address both short-term and long-term security problems spanning several disciplines. Group members are focused on developing new security technologies to ensure the safety of all facets of the communication and computation infrastructure bridging the gap between cutting edge research and solid engineering practices, thus, providing the perfect setting for the education of next generation security experts. http://v.wpi.edu/

Wireless Innovation Laboratory (WILab)

Prof. Wyglinski

The Wireless Innovation Laboratory (WILab) conducts fundamental and applied research in wireless communication systems engineering and vehicular technology. Consisting of approximately 750 sq ft of prime research space as well as state-of-the-art software tool and experimentation equipment, this facility focuses on devising new solutions and new knowledge in the areas of cognitive radio, connected vehicles, software-defined radio, autonomous vehicles, wireless spectrum and resource allocation, vehicular security, prototype wireless systems, vehicular networking,

ECE Graduate Course Chart 2017-18



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cyber-physical systems, and advanced signal processing algorithms. WILab has been extensively funded via numerous sponsors from both government and industry, including the National Science Foundation, MathWorks, Office of Naval Research, Toyota InfoTechnology Center USA, and the MITRE Corporation. For more details, please see the WILab website at http://www.Wireless.WPI.edu.

Course Descriptions

All courses are 3 credits unless otherwise noted.

ECE 502. Analysis of Probabilistic Signals and Systems

Applications of probability theory and its engineering applications. Random variables, distribution and density functions. Functions of random variables, moments and characteristic functions. Sequences of random variables, stochastic convergence and the central limit theorem. Concept of a stochastic process, stationary processes and ergodicity. Correlation functions, spectral analysis and their application to linear systems. Mean square estimation. (Prerequisite: Undergraduate course in signals and systems.)

ECE 503. Digital Signal Processing

Discrete-time signals and systems, frequency analysis, sampling of continuous time signals, the z-transform, implementation of discrete time systems, the discrete Fourier transform, fast Fourier transform algorithms, filter design techniques. (Prerequisites: Courses in complex variables, basic signals and systems.)

ECE 504. Analysis of Deterministic Signals and Systems

Review of Fourier series and linear algebra. Fourier transforms, Laplace transforms, Z transforms and their interrelationship. State space modeling of continuous-time and discrete-time systems. Canonical forms, solution of state equations, controllability, observability and stability of linear systems. Pole placement via state feedback, observer design, Lyapunov stability analysis. (Prerequisite: Undergraduate course in signals and systems.)

ECE 505. Computer Architecture

This course introduces the fundamentals of computer system architecture and organization. Topics include CPU structure and function, addressing modes, instruction formats, memory system organization, memory mapping and hierarchies, concepts of cache and virtual memories, storage systems, standard local buses, high-performance I/O, computer communication, basic principles of operating systems, multi-programming, multiprocessing, pipelining and memory management. The architecture principles underlying RISC and CISC processors are presented in detail. The course also includes a number of design projects, including simulating a target machine, architecture using a high-level language (HLL). (Prerequisites: Undergraduate course in logic circuits and microprocessor system design, as well as proficiency in assembly language and a structured high-level language such as C or Pascal.)

ECE 506. Introduction to Local and Wide Area Networks

This course provides an introduction to the theory and practice of the design of computer and communications networks, including the ISO seven-layer reference model. Analysis of network topologies and protocols, including performance analysis, is treated. Current network types and evolving network technologies are introduced, including local, metropolitan and wide area networks. The theory, design and performance of local area networks are emphasized. The course includes an introduction to queueing analysis and network programming. (Prerequisites: A knowledge of the C programming language is assumed. CS 504 or ECE 502 or equivalent background in probability; may be taken concurrently. NOTE: Students who received credit for ECE 573 may not receive credit for ECE 506.)

ECE 5105. Introduction to Antenna Design

This course is intended for graduate and senior-level undergraduate students. The course provides an introduction to major antennas and antenna types for wireless communications, electrical and biomedical sensors, and RF and MW engineering. Basic antenna characteristics are studied: polarization, directivity, gain, realized gain, and impedance bandwidth. Both narrowband and broadband antennas as well as linear and planar antenna arrays are considered. An emphasis is made on learning modern antenna modeling software– ANSYS HFSS and Antenna Toolbox of MATLAB. The course structure is directed toward practical antenna design and enables senior undergraduate students to take this course. Course topics include: transmitter-receiver antenna circuit models, antenna radiation and radiation parameters, dipole antenna family, patch antenna family, loop antenna family, reflector antennas, small antennas, antenna matching and tuning, antenna arrays, on-body and in-body antennas. (Prerequisites: undergraduate analog electronics, college MATLAB, and basic introductory knowledge of electromagnetic theory - ECE 2019 and ECE 3113).

ECE 5106. Modeling of Electromagnetic Fields in Electrical & Biological Systems

This course is intended for graduate and senior-level undergraduate students. Modern numerical methods and major software packages are reviewed in application to modeling electrical and biomedical sensors, bioelectromagnetics, wireless communications (including wireless body area networks), and power electronics. The course begins with an introduction to computational mesh generation. Triangular surface meshes, volumetric tetrahedral meshes, voxel meshes, and computational human phantoms are studied. The boundary element method or the method-of-moments is introduced and detailed, followed by a review of the finite element method for electromagnetic problems. The finite-difference time-domain method is another major topic of the course. The course also covers ray tracing algorithms in application to wireless networks. (Prerequisites: college MATLAB, differential and integral calculus).

ECE 514. Fundamentals of RF and MW Engineering

This introductory course develops a comprehensive understanding of Maxwell's field theory as applied to high-frequency radiation, propagation and circuit phenomena. Topics include radio-frequency (RF) and microwave (MW) propagation modes, transmission line aspects, Smith Chart, scattering parameter analysis, microwave filters, matching networks, power flow relations, unilateral and bilateral amplifier designs, stability analysis, oscillators circuits, mixers and microwave antennas for wireless communication systems. (Prerequisites: ECE 504 or equivalent, undergraduate course in electromagnetic field analysis.)

ECE 5204. Analog Circuits and Intuition

The ability to see the simplicity in a complex design problem is a skill that is not usually taught in engineering classes. Some engineers, when faced with design problems, immediately fill up pages and pages of calculations, or do complex circuit simulations or finite-element analyses. One problem with this approach is that if you get an answer, you do not know if it is correct unless you have an intuitive "feel" for what the answer should be. The application of some simple rules of thumb and design techniques is a possible first step to developing intuition into the behavior of complex electrical systems. This course outlines some ways of thinking about analog circuits and systems that are intended will help to develop intuition and guide design. The lectures are a mixture of instructional sessions covering new background material, and design case studies. (Prerequisites: Undergraduate background in device physics, microelectronics, control systems, electromagnetism)

ECE 523. Power Electronics

The application of electronics to energy conversion and control. Electrical and thermal characteristics of power semiconductor devices—diodes, bipolar transistors and thyristors. Magnetic components. State-space averaging and sampled-data models. Emphasis is placed on circuit techniques. Application examples include dc-dc conversion, controlled rectifiers, high-frequency inverters, resonant converters and excitation of electric machines. (Prerequisites: ECE 3204 and undergraduate courses in modern signal theory and control theory; ECE 504 is recommended.)

ECE 524. Advanced Analog Integrated Circuit Design

This course is an advanced introduction to the design of analog and mixed analog-digital integrated circuits for communication and instrumentation applications. An overview of bipolar and CMOS fabrication processes shows the differences between discrete and integrated circuit design. The bipolar and MOS transistors are reviewed with basic device physics and the development of circuit models in various operating regions. The use of SPICE simulation in the design process will be covered. Integrated amplifier circuits are developed with an emphasis on understanding performance advantages and limitation in such areas as speed, noise and power dissipation. Simple circuits are combined to form the basic functional building blocks such as the op-amp, comparator, voltage reference, etc. These circuit principles will be explored in an IC design project, which may be fabricated in a commercial analog process. Examples of possible topics include sample-and-hold (S/H) amplifier, analog-to-digital (A/D) and digital-to-analog (D/A) converters, phase-locked loop (PLL), voltage-controlled oscillator, phase detector, switched capacitor and continuous-time filters, and sampled current techniques. (Prerequisite: Background in analog circuits both at the transistor and functional block [op-amp, comparator, etc.] level. Also familiarity with techniques such as small-signal modeling and analysis in the s-plane using Laplace transforms. Undergraduate course equivalent background ECE 3204; ECE 4902 helpful but not essential.)

ECE 529. Selected Topics in Electronic System Design

Courses in this group are devoted to the study of advanced topics in electronic system design.

ECE 530/CS 530. High Performance Networks

This course is an in-depth study of the theory, design and performance of high-speed networks. Topics include specifi c high-performance network architectures and protocols and emerging technologies including multimedia networks and quality-of- service issues. Topics associated with interconnecting networks such as bridges and routers will also be discussed. Performance analysis of networks will include basic queueing models. (Prerequisite: ECE 506/CS 513.)

ECE 5307. Wireless Access and Localization

This course covers the fundamentals of the evolving wireless localization techniques and their relation with the wireless access infrastructures for Electrical and Computer Engineering, Computer Science or other graduate students interested in this field. The course begins with an explanation of the common ground among wireless access and localization techniques which are principles of waveform transmission in multipath rich urban and indoor areas and the deployment of the infrastructure for wireless networks. This is followed by the fundamentals of received signal strength (RSS) and Time- and Angle-of-arrival (TOA/AOA) based localization techniques, addressing applications, systems, effects of environment, performance bounds and algorithms. The course describes how wireless access methods used in wide, local and personal area networks are related to localization techniques using cellular, UWB, WiFi, and other signals of opportunity as well as mechanical sensors used in different smart phone and Robotic platforms. The emphasis on the effects of environment is on the analysis of the effects of multipath on precision of the localization techniques. The emphasis on performance evaluation is on the derivation of Cramer Rao Lower Bound (CRLB). For algorithms, the course describes fingerprinting algorithms used for RSS-based localization and super-resolution, cooperative localization, localization using multi-carrier transmission and localization using multipath diversity as well as Kalman and Particle filtering techniques used for model based localization. Examples of emerging technologies in Body Area Networking and Robotics applications are provided. (Prerequisite: ECE 506, CS 513, or equivalent familiarity with local and wide area networks.)

ECE 531. Principles of Detection and Estimation Theory

Detection of signals in noise, optimum receiver principles, M-ary detection, matched filters, orthogonal signals and representations of random processes. MAP and maximum likelihood estimation. Wiener filtering and Kalman filtering. Channel considerations: prewhitening, fading and diversity combining. (Prerequisites: ECE 502 and ECE 504 or equivalent.)

ECE 5311. Information Theory and Coding

This course introduces the fundamentals of information theory and discusses applications in compression and transmission of data. Measures of information, including entropy, and their properties are derived. The limits of lossless data compression are derived and practical coding schemes approaching the theoretical limits are presented. Lossy data compression tradeoffs are discussed in terms of the rate-distortion framework. The concept of reliable communication through noisy channels (channel capacity) is developed. Techniques for practical channel coding, including block and convolutional codes, are also covered. (Prerequisite: background in probability and random processes such as in ECE502 or equivalent).

ECE 5312. Modern Digital Communications

This course introduces a rigorous analytical treatment of modern digital communication systems, including digital modulation, demodulation, and optimal receiver design. Error performance analysis of these communication systems when operating over either noisy or band-limited channels will be conducted. Advanced topics to be covered include a subset of the following: MIMO, fading channels, multiuser communications, spread spectrum systems, and/or multicarrier transmission. (Prerequisites: An understanding of probability and random processes theory (ECE 502 or equivalent); an understanding of various analog and digital (de)modulation techniques (ECE 3311 or equivalent); familiarity with MATLAB programming.

ECE 5341. Applied Medical Signal Analysis

This course provides a broad introduction to medical signal analysis, particularly tailored to students who have no prior background in physiology or medicine. The course will concentrate on signal analysis of the electrical activity of the human body, providing sufficient physiologic background for study of the relevant organ systems. System-level engineering models of the electrical activity of the heart, skeletal muscles and brain will be presented and actual physiologic signals will be analyzed. Digital signal processing algorithms for analysis of these signals will be studied extensively using MATLAB. Specific signal processing topics may include: use of muscle electrical activity to command powered prostheses and/or guide rehabilitation therapy; design of filters to reject motion artifact, noise and interference; monitoring (e.g., detection and classification) of heart, brain and muscle electrical impulses; and non-invasive estimation of muscle activation level. Students may not receive credit for ECE 5341 and either ECE 443X or ECE 539D. (Prerequisites: Undergraduate (or graduate) course in digital signal processing, experience with MATLAB and a course in probability.)

ECE 537/CS 577. Advanced Computer and Communications Networks

This course covers advanced topics in the theory, design and performance of computer and communication networks. Topics will be selected from such areas as local area networks, metropolitan area networks, wide area networks, queuing models of networks, routing, flow control, new technologies and protocol standards. The current literature will be used to study new networks concepts and emerging technologies. (Prerequisite: ECE 506/CS 513 and ECE 581/CS 533.)

ECE 538. Wireless Information Networks

Overview of wireless information networks and personal communications systems: digital cellular, wireless PBX, cordless phone, wireless LAN, and mobile data, multimedia wireless and directions of the future. Radio propagation modeling for urban and indoor radio channels, coverage interface and cell size. Modulation techniques for efficient use of bandwidth resources. Methods to increase the data rate: antenna diversity and sectorization, adaptive equalization, multirate transmission and multiamplitude phase modulation. Spread spectrum for digital cellular, personal communications and wireless LAN applications. TDMA, CDMA, ALOHA, and CSMA, DECT, GSM, USDC, JDC, IEEE 802.11, WINForum, and HIPERLAN. (Prerequisite: Background in networks. Familiarity with probability, statistics and signal processing).

ECE 539. Selected Topics in Communication Theory and Signal Processing

Courses in this group are devoted to the study of advanced topics in in Communication Theory and Signal Processing.

ECE 545/CS 545. Digital Image Processing

See CS 545 course description.

ECE 549. Selected Topics in Control

Courses in this group are devoted to the study of advanced topics in the formulation and solution of theoretical or practical problems in modern control.

ECE 5500. Power System Analysis

This graduate level course examines the principles of Power System Analysis. It will begin with a review of AC circuit analysis. The course will then cover the topics of transmission line parameter calculation, symmetrical component analysis, transformer and load modeling, symmetrical and unsymmetrical fault analysis, power flow, and power systems stability. (Prerequisites: Knowledge of circuit analysis, basic calculus and differential equations, elementary matrix analysis and basic computer programming.)

ECE 5510. Power Quality

This graduate level course provides detailed explanations of the physical mechanisms that control phenomena related to Power Quality. It addresses concepts that underlie harmonic generation and harmonic flow, and the modeling of voltage sags and swells. The effects of such disturbances on equipment (transformers, rotating machines, lamps, relays and converters) performance are studied by means of actual field cases. Frequency response of the grid, resonances and ferroresonances as well as electromagnetic interference are studied. Mitigation methods using advanced transformers connections, static, hybrid and active filters are modeled using real-life examples. Others topics covered are Power Quality measurements in the era of smart grid, Power Quality problems caused by Renewable Generators, and Engineering Economics issues related to Power Quality. (Prerequisites: ECE 5500 Power System Analysis. Also, this course presumes that the student has an understanding of basic electronics.)

ECE 5511. Transients in Power Systems

This graduate level course introduces the student to the effects of electromagnetic transients in distribution systems. Topics include transient analysis, lightning and switching surges, mechanisms of transient generation, insulation coordination, grounding, surge protection devices, and shielding. (Prerequisite: ECE 5500 Power System Analysis)

ECE 5512. Electromechanical Energy Conversion

This graduate level course will further explore alternating current circuits, three phase circuits, basics of electromagnetic field theory, magnetic circuits, inductance, and electromechanical energy conversion. Topics also include ideal transformer, iron-core transformer, voltage regulation, efficiency equivalent circuit, and three phase transformers. Induction machine construction, equivalent circuit, torque speed characteristics, and single phase motors, synchronous machine construction, equivalent circuit, power relationships phasor diagrams, and synchronous motors will be covered. Direct current machine construction, types, efficiency, power flow diagram, and external characteristics will be discussed.

ECE 5520. Power System Protection and Control

This graduate level course seeks to provide an understanding of how interconnected power systems and their components are protected from abnormal events such as faults (short circuits), over-voltages, off-nominal frequency and unbalanced phase conditions. This subject is presented from a theoretical viewpoint, however, many practical examples and applications are included that emphasize the limitations of existing protective equipment. Course content is not specific to any particular manufacturer's equipment.

The course begins with a brief review of power system operation, three-phase system calculations and the representation (modeling) of power system elements. The modeling of current transformers under steady-state and transient conditions is presented with emphasis on the impact on protective devices. A unit on system grounding and its impact on protective device operation are included. Course emphasis then shifts to protective devices and their principles of operation. Both electromechanical and numeric relay designs are covered. The final course segments cover specific applications such as pilot protection of transmission lines, generator protection and transformer protection. (Prerequisite: ECE 5500 Power System Analysis)

ECE 5521. Protective Relaying

This graduate level course is the first of a two course sequence that covers both the principles and practices of power system protective relaying. The course seeks to provide an understanding of how interconnected power systems and their components are protected from abnormal events such as faults (short circuits), over-voltages, off-nominal frequency and unbalanced phase conditions. This subject is presented from a theoretical viewpoint, however, many practical examples are included that emphasize the limitations of existing protective equipment. Course content is not specific to any particular manufacturer's equipment. The course begins with a brief review of the nature of power system operation, power system faults and other abnormal conditions. The nature and objectives of protective relaying are covered next with emphasis on how the power system can be monitored to detect abnormal conditions. The computational tools needed to analyze system operation and apply protective relaying are covered next, including the per-unit system, phasors and symmetrical components. The modeling of current transformers under steady-state and transient conditions is presented with emphasis on the impact on protective devices. A unit on system grounding and its impact on protective device operation is included. Course emphasis then shifts to protective devices and their principles of operation. Both electromechanical and numeric relay designs are covered. (Prerequisite: ECE 5500 Power System Analysis or equivalent background experience is suggested. Familiarity with phasors, derivatives, transfer functions, poles and zeros, block diagram and the notion of feedback with basic understanding power system analysis or similar background is recommended. Note: Credit cannot be awarded for this course if credit has already been received for ECE 5520 Power System Protection and Control.)

ECE 5522. Advanced Applications in Protective Relaying

This graduate level course covers advanced topics in the principles and practices of power system protective relaying. The course seeks to provide an understanding of how protective relays are applied to protect power system components. While the subject is presented from a theoretical viewpoint, many practical examples are included. Examples specific to both new installations and existing, older facilities will be included. Course content is not specific to any particular manufacturer's equipment. The course begins with applications of protective devices to generators. This will include distributed generation as well as wind-turbine and inverter-connected sources. Transformer protection is covered next, including application procedures for older, electromechanical relays as well as modern numeric relay designs. A unit on bus protection is covered next, including all typical high-speed and time backup bus protection schemes. Transmission line and distribution feeder protection is covered in detail including both conventional and communications-assisted schemes. The course ends with a unit on other protection applications such as under frequency load shedding, reclosing and out-of-step relaying. (Prerequisite: ECE 5521 Protective Relaying. Note: Credit cannot be awarded for this course if credit has already been received for ECE 5520 Power System Protection and Control.)

ECE 5523. Power System Dynamics

This graduate level course is concerned with modeling, analyzing and mitigating power system stability and control problems. The course seeks to provide an understanding of the electromechanical dynamics of the interconnected electric power grid. This subject is presented from a theoretical viewpoint; however, many practical examples are included. The course begins with a description of the physics of the power system, frequency regulation during "steady-state" operation, dynamic characteristics of modern power systems, a review of feedback control systems, power system frequency regulation, and a review of protective relaying. This is followed by material on synchronous machine theory and modeling. Simulation of power system dynamic response, small signal stability, transient stability analysis using SIMULINK and effects of non-traditional power sources on systems dynamics will also be covered. Power system stabilizers, load modeling

and under frequency load shedding are covered in the final lectures. (Prerequisite: ECE 5500 Power System Analysis and ECE 5511 Transients in Power Systems or equivalent background experience is suggested. Familiarity with the basics of Laplace Transforms, derivatives, transfer functions, poles and zeros, block diagram and the notion of feedback with basic understanding power system analysis topics recommended.)

ECE 5530. Power Distribution

This graduate level course introduces the fundamentals of power distribution systems, apparatus, and practices suited to new and experienced utility distribution engineers. Topics include distribution system designs, transformers and connections, practical aspects of apparatus and protection, principles of device coordination, grounding, voltage control, and power quality. (Prerequisites: Prior courses in magnetism and three-phase circuits. An electric machines course would be recommended.)

ECE 5531. Power System Operation and Planning

This graduate-level course deals with modern operation, control and planning for power systems. Topics include: Characteristics of generating units; Economic Dispatch; Unit Commitment; Effects of the transmission system on power delivery; Optimal Power Flow and Location Marginal Pricing; Power System Security; State Estimation for Power Systems; Power System Reliability Evaluation. Software tools such as MATLAB and power system simulator software will be used both in the classroom and in some homework assignments.

ECE 5532. Distributed and Renewable Power Generation

This course introduces the characteristics and challenges of interconnecting increasing numbers of Distributed Energy Resources (DERs) to the Electric Power System (EPS). Topics include: challenges to distribution and transmission system protection; local voltage control; ride through; optimal interconnection transformer configurations; and practical engineering approaches to maintain system reliability and protection. The current and evolving interconnection standard (IEEE 1547) is included. Prerequisites: Since the course material builds on power system analysis capabilities, including system protection and controls, ECE 5500 Power System Analysis and either ECE 5520 Power System Protection & Control or ECE 5521 Protective Relaying are required. Also, it is recommended that students take this course after completing ECE 5530 Power Distribution.

ECE 5540. Power Transmission

This graduate level course focuses on the theory and current professional practice in problems of electric power transmission. It begins with a review of the theory of AC electric power transmission networks and addresses a range of challenges related to reactive power and voltage control as well as steady-state and transients stability. Students will learn in detail the principles of traditional reactive power compensation (shunt reactors and capacitors); series compensation and modern static reactive compensation like SVC, STATCOM and other Flexible AC Transmission Systems (FACTS) devices. The effects of each of these types of compensation on static and dynamic voltage control, reactive power requirement and steady-state and transient stability problems are covered from theoretical as well as practical aspects. Particular attention is given to the mathematical models and principles of operation of many types of compensation systems. Basic principles of operation and control of High-Voltage DC (HVDC) systems and their impact on steady-state and dynamics of power system will be covered as well. (Prerequisite: ECE 5500 Power System Analysis.)

ECE 5599. Capstone Project Experience in Power Systems

This project-based course integrates power systems engineering theory and practice, and provides the opportunity to apply the skills and knowledge acquired in the Power Systems curriculum. The project is normally conducted in teams of two to four students. Students are encouraged to select projects with practical significance to their current and future professional responsibilities. The projects are administered, advised, and evaluated by WPI faculty as part of the learning experience, but students are also encouraged to seek mentorship from experienced colleagues in the Power Systems profession. (Prerequisites: Since the Capstone Project will draw on knowledge obtained throughout the degree program, it is expected that the student will have completed most or all of the coursework within their plan of study before undertaking the capstone project.)

ECE 559. Selected Topics in Energy Systems

Courses in this group are devoted to the study of advanced topics in energy systems. Typical topics include optimal power flow, probability methods in power systems analysis, surge phenomena, design of electrical apparatus, transient behavior of electric machines and advanced electromechanical energy conversion.

ECE 566. VLSI Design

VLSI Design introduces computer engineers and computer scientists to the techniques, methodologies and issues involved in conceptual and physical design of complex digital integrated circuits. The course presupposes knowledge of computer systems and hardware design such as found in ECE 505, but does not assume detailed knowledge of transistor circuits and physical electronics. (Prerequisite: ECE 505 or equivalent.)

ECE 569. Selected Topics in Solid State

Courses in this group are devoted to the study of advanced topics in solid state, for example: degenerate semiconductors, many-body theory, elastic effects and phonon conduction, and solar cells. To reflect changes in faculty research interests, these courses may be modified or new courses may be added.

ECE 5715. Reconfigurable Computing

This course focused on the principles and applications of using FPGAs for reconfigurable computing. The key feature of reconfigurable computing is its ability to perform computations in customized hardware, while retaining much of the flexibility of a software solution. This course provides an overview of field programmable gate array (FPGA) architecture and technology. It introduces computer-aided design tools for FPGAs including synthesis, timing, placement, and routing. The course emphasizes on the techniques to analyze algorithms and to implement them on the FPGAs. It demonstrates real-time signal and data processing in customized hardware circuits. This course also covers system-on-chip design using the embedded processors inside the FPGAs. Partially reconfiguration and runtime reconfiguration design flow are also included.

ECE 572/CS 514. Advanced Systems Architecture

This course covers techniques such as caching, hierarchical memory, pipelining and parallelism, that are used to enhance the performance of computer systems. It compares and contrasts different approaches to achieving high performance in machines ranging from advanced microprocessors to vector supercomputers (CRAY, CYBER). It also illustrates how these techniques are applied in massively parallel SIMD machines (DAP, Connection Machine). In each case the focus is on the combined hardware /software performance achieved and the interaction between application demands and hardware/software capabilities. (Prerequisites: This course assumes the material covered in ECE 505. The student should also have a background in computer programming and operating systems (CS 502). Familiarity with basic probability and statistics such as ECE 502 or MA 541 is recommended.)

ECE 5720. Modeling and Synthesis of Digital Systems Using Verilog

Automatic design, synthesis, verification, and modeling of complex digital systems with Verilog are the main course objectives. Verilog for modeling existing circuits, as well as Verilog for design and automatic synthesis is discussed. Using Verilog for a design that consists of a hierarchy of components that include controllers, sequential and combinational parts is focused. Design description from transistor level to software interface will be discussed. Students will learn details of hardware of processor architectures and their peripherals. The course discusses module delay adjustments using Verilog path delay and distributed delay mechanisms. Testbench development and assertion verifications will be discussed. Students will learn to simulate verify, synthesize, and program their designs on an Altera development board using advanced Altera FPGAs. (Prerequisite: Undergraduate knowledge of basic logic design concepts. ECE 574 may be substituted for ECE 5720. Students may not receive credit for both ECE 574 and ECE 5720). For students not having the necessary background, online videos will be made available to cover the prerequisites.

ECE 5722. Embedded Core Architectures and Core-based Design

This course introduces the concept of design with embedded components. Embedded processors, IP cores, and bus structures are discussed here. Embedded processor architectures, architectures for arithmetic processors, I/O interfacing modules, memory interfacing, and architectures related to busses and switch fabrics for putting a complete embedded system are discussed here. Topics include RT level design, arithmetic processors, ISA, CPU structure and function, addressing modes, instruction formats, memory system organization, memory mapping and hierarchies, concepts of cache, standard local buses, IO devices, pipelining, memory management, embedded processors, embedded environments, bus and switch fabrics, and embedded system implementation. An example embedded design environment including its configurable cores and processors and its bus structure will be presented in details. The course also includes a number of design projects, including design and simulation of an embedded processor, design of an arithmetic core, and design of a complete embedded system. (Prerequisite: Familiarity with C programming, Undergraduate knowledge of basic logic design concepts, familiarity with a hardware description language). Note: For students not having the necessary background, online videos will be made available to cover the prerequisites.

ECE 5723. Methodologies for System Level Design and Modeling

This course discusses principles, methodologies and tools used for a modern hardware design process. Design flows and hardware languages needed for each stage of the design process are discussed. The use of transaction level modeling (TLM) for dealing with today's complex designs is emphasized. The course starts with a discussion of the evolution of hardware design methodologies, and then discusses the use of C++ for an algorithmic description of hardware. SystemC and its TLM derivative and the role of SystemC in high-level design will be discussed. In addition, RT level interfaces and the use of SystemC for this level of design will be covered. Timed, untimed, and approximately timed TLM models and modeling schemes will be presented. Use of TLM for fast design simulation, design space exploration, and high-level synthesis will be discussed. TLM testing methods and testing of TLM based NoCs will be discussed. The course starts with a complete design project and exercises various parts of this design as methodologies, concepts, and languages are discussed. Specific topics covered are as follows: Levels of abstraction C++ for digital design SystemC RT level and above TLM methodology TLM timing aspects TLM channels TLM channels Mixed level design NoC TLM modeling System testing

ECE 5724. Digital Systems Testing and Testable Design

This course discusses faults and fault modeling, test equipment, test generation for combinational and sequential circuits, fault simulation, memory testing, design for testability, built-in self-test techniques, boundary scan, IEEE 1149.1, and board and SoC test standards. Various fault simulation and ATPG methods including concurrent fault simulation, D-algorithm, and PODEM are discussed. Controllability and observability methods such as SCOAP for testability analysis are discussed. Various full-scan and partial scan methods are described and modeled in Verilog and tested with Verilog testbenches. BIST architectures for processor testing, memory testing and general RT level hardware testing are described, modeled in Verilog and simulated and evaluated for fault coverage. The course uses Verilog testbenches for simulating golden models, developing and evaluating test sets, and for mimicking testers. (Recommended prerequisites: Understanding digital systems and design of combinational and sequential circuits, Understanding a hardware description language (VHDL or Verilog) and the use of these languages for simulation and synthesis.)

ECE 574. Modeling and Synthesis of Digital Systems Using Verilog and VHDL

This is an introductory course on Verilog and VHDL, two standard hardware description languages (HDLs), for students with no background or prior experience with HDLs. In this course we will examine some of the important features of Verilog and VHDL. The course will enable students to design, simulate, model and synthesize digital designs. The dataflow, structural, and behavioral modeling techniques will be discussed and related to how they are used to design combinational and sequential circuits. The use of test benches to exercise and verify the correctness of hardware models will also be described. Course Projects: Course projects will involve the modeling and sysntesis and testing of systems using Xilinx tools. We will be targeting Xilinx FPGA and CPLDs. Students will need to purchase a FPGA or CPLD development board for project assignments. (Other VHDL tools may be used if these are available to the student at their place of employment.) Students will have the choice of completing assignments in either Verilog or VHDL. (Prerequisites: Logic Circuits and experience with programming in a high-level language (such as C or Pascal) and a computer architecture course such as ECE 505.) Students cannot receive credit for both ECE 574 and ECE 5720

ECE 578/CS 578. Cryptography and Data Security

This course gives a comprehensive introduction to the field of cryptography and data security. The course begins with the introduction of the concepts of data security, where classical algorithms serve as an example. Different attacks on cryptographic systems are classified. Some pseudo-random generators are introduced. The concepts of public and private key cryptography are developed. As important representatives for secret key schemes, DES and IDEA are described. The public key schemes RSA and ElGamal, and systems based on elliptic curves are then developed. Signature algorithms, hash functions, key distribution and identification schemes are treated as advanced topics. Some advanced mathematical algorithms for attacking cryptographic schemes are discussed. Application examples will include a protocol for security in a LAN and a secure smart card system for electronic banking. Special consideration will be given to schemes which are relevant for network environments. For all schemes, implementation aspects and up-to-date security estimations will be discussed. (Prerequisites: Working knowledge of C; an interest in discrete mathematics and algorithms is highly desirable. Students interested in a further study of the underlying mathematics may register for MA 4891 [B term], where topics in modern algebra relevant to cryptography will be treated.)

ECE 579. Selected Topics in Computer Engineering

Courses in this group are devoted to the study of advanced topics in computer engineering such as real-time intelligent systems, VLSI design and high-level languages.

ECE 581/CS 533. Modeling and Performance Evaluation of Network and Computer Systems

Methods and concepts of computer and communication network modeling and system performance evaluation. Stochastic processes; measurement techniques; monitor tools; statistical analysis of performance experiments; simulation models; analytic modeling and queueing theory; M/M, Erlang, G/M, M/G, batch arrival, bulk service and priority systems; work load characterization; performance evaluation problems. (Prerequisites: CS 504 or ECE 502, or equivalent background in probability.)

ECE 5905. Advanced Bipolar Solid State Devices

The operation of the bipolar junction transistor (BJT) will be explored in detail, resulting in thorough understanding of observed phenomena including second-order effects that limit device performance in practical integrated circuit applications. The course begins with a review of semiconductor fundamentals and p-n junction behavior, followed by extension to the BJT, with an emphasis on effects such as temperature dependence of operation parameters, deviations from ideal behavior at high and low voltages and currents, and failure modes such as zener and avalanche breakdown. BJT behavior will be modeled for large and small signals under DC, AC, and transient conditions. Results from theoretical hand-analysis equations will be correlated with model parameters in software tools such as SPICE. Implications of fabrication technology including device scaling in submicron processes will be considered. This course is intended for students pursuing study in either integrated circuit design or device physics. (Prerequisite: undergraduate analog electronics).

ECE 596A and ECE 596B. Graduate Seminars

The presentations in the graduate seminar series will be of tutorial nature and will be presented by recognized experts in various fields of electrical and computer engineering. All full-time graduate students will be required to take both seminar courses, ECE 596A and ECE 596B, once during their graduate studies in the Electrical and Computer Engineering Department. The course will be given Pass/Fail. (Prerequisite: Graduate standing.)

ECE 597. Independent Study

Approved study of a special subject or topics selected by the student to meet his or her particular requirements or interests. Can be technical in nature, or a review of electrical and computer engineering history and literature of importance and permanent value. (Prerequisite: B.S. in ECE or equivalent.)

ECE 598. Directed Research

Each student will work under the direct supervision of a member of the department staff on an experimental or theoretical problem which may involve an extensive literature search, experimental procedures and analysis. A comprehensive report in the style of a technical report or paper and an oral presentation are required. (A maximum of two registrations in ECE 598 is permitted.) (Prerequisite: Graduate standing.)

ECE 599. Thesis

ECE 630. Advanced Topics in Signal Processing

The course will cover a set of important topics in signal and image analysis: orthogonal signal decomposition, wavelet transforms, analytic signals, time-frequency estimation, 2D FT, Hankel transform and tomographic reconstruction. In addition, the course will each year have selected current topics in signal processing, e.g., ambiguity functions in RADAR and SONAR, coded waveforms, Fourier based beamforming for 2D arrays and single value decomposition. In place of a final exam, there will be a student project. The course is intended for students working in areas such as image analysis, NDE, ultrasound, audio, speech, RADAR, SONAR and date compression. Signal/image theory and applications will be emphasized over coding; however, Matlab-based modules for self-paced signal/image visualization and manipulation will be part of the course. (Prerequisites: ECE 504 Analysis of Deterministic Signals and Systems, undergraduate course in linear systems theory and vector calculus.)

ECE 673. Advanced Cryptography

This course provides deeper insight into areas of cryptography which are of great practical and theoretical importance. The three areas treated are detailed analysis and the implementation of cryptoalgorithms, advanced protocols, and modern attacks against cryptographic schemes. The first part of the lecture focuses on public key algorithms, in particular ElGamal, elliptic curves and Diffie-Hellman key exchange. The underlying theory of Galois fields will be introduced. Implementation of performance security aspects of the algorithms will be looked at. The second part of the course deals with advanced protocols. New schemes for authentication, identification and zero-knowledge proof will be introduced. Some complex protocols for real-world application— such as key distribution in networks and for smart cards—will be introduced and analyzed. The third part will look into state-of-the-art cryptoanalysis (i.e., ways to break cryptosystems). Brute force attacks based on special purpose machines, the baby-step giant-step and the Pohlig-Hellman algorithms will be discussed. (Prerequisites: ECE 578/ CS 578 or equivalent background.)

ECE 699. Ph.D. Dissertation

Fire Protection Engineering

Faculty

Core FPE Program Faculty

T. El-Korchi, Professor and Department Head; Ph.D., University of New Hampshire. Civil engineering, statistics, strength of materials, structural design, construction materials, structural analysis, structural materials, pavement analysis, design and management.

N. A. Dembsey, Professor; Ph.D., University of California at Berkeley; Fire properties of materials and protective clothing via bench-top scale experimentation; compartment fire dynamics via residential scale experimentation, evaluation, development and validation of compartment fire models, performance fire codes, engineering design tools, and engineering forensic tools.

B. J. Meacham, Associate Professor; Ph.D., Clark University; risk and public policy, performance-based design, risk concepts in regulation, uncertainty in egress modeling.

K. A. Notarianni, Associate Professor; Ph.D., Carnegie Mellon University; Fire detection and suppression; high-bay fire protection; fire policy and risk; uncertainty; performance-based design; engineering tools for the fire service.

M. T. Puchovsky, Professor of Practice; fire engineering design practices, codes and standards development, loss control, life safety code and design, performance-based design and risk analysis, fire investigation and litigation support, fire protection systems.

A. Rangwala, Professor, Ph.D., University of California, San Diego; combustion, flame spread on solid fuels and compartment fire modeling, dust explosions, risk assessment of Liquefied Natural Gas (LNG) transport and storage, industrial fire protection.

A. Simeoni, Associate Professor; Ph.D., University of Corsica; modeling, simulation and experiments of wildfires, heat and mass transfer, fire fighting and land management.

Associated FPE Program Faculty

L. Albano, Associate Professor; Ph.D., Massachusetts Institute of Technology; Performance of structural members, elements, and systems at elevated temperatures; structural design for fire conditions; simplified or design office techniques for fire-structure interaction; relationship between building construction systems and fire service safety.

Adjunct FPE Faculty

R. Alpert, Adjunct Professor; Sc.D., Massachusetts Institute of Technology; combustion gas dynamics, combustion-induced instabilities about blunt-body projectiles, fire dynamics, reduced-scale modeling, enclosure fires; numerical modeling of the interactions between fire flows and sprinkler droplet sprays.

N. Kazantsis; Ph.D., University of Michigan/Ann Arbor; energy and environmental systems analysis, chemical process safety, risk characterization, regulation of chemicals.

W. Krein, Adjunct Assistant Professor; Fire Protection Engineering and School of Business; organizational behavior, entrepreneurship, corporate financial management, mergers and acquisitions, consulting, engineering economics, project management.

W. Shields, Adjunct Associate Professor; Ph.D., Virginia Tech; Juris Doctorate, Columbia University School of Law; nuclear engineering, law/science interfaces, astrophysics and applied mathematics, Defense Nuclear Facilities Safety Board, Assistant General Counsel-Nuclear Regulatory Commission.

J. Tubbs, Adjunct Assistant Professor; Consulting, large unique building design, smoke control systems, detection and alarm, egress from fire.

C. Wood, Adjunct Associate Professor; Licensed attorney, fire protection engineering, expert witness testimony, fire modeling and dynamics. Fire investigation, failure analysis of fires and explosions.

FPE Emeritus

R. W. Fitzgerald, Professor Emeritus; Ph.D., University of Connecticut; structural aspects of fire safety, building analysis and design for fire safety, marine fire safety, building codes, real estate development, fire department operations, risk management.

D. A. Lucht, Director Emeritus; building codes and regulatory reform, building fire safety analysis and design, professional practice.

R. Zalosh; Professor Emeritus, Ph.D., Northeastern University; Fire and explosion hazards associated with flammable gases, liquids, and powders. Fire/explosion protection methods and systems designed to deal with these special hazards. Theoretical, experimental, and risk-based engineering tools for addressing these issues.

Research Interests

WPI is a recognized world leader in a wide range of topics in fire protection engineering and related areas. Research is directed toward both theoretical understandings and the development of practical engineering methods. WPI faculty and their students create new knowledge that informs and shapes regulatory policy, building design, product manufacturing, and product performance standards.

Specific capabilities and interests include: fire and material;, combustion and explosion protection; computer modeling; fire performance of structural systems; fire detection and suppression; fire and smoke dynamics; wildland urban interface fires; regulatory policy, risk, and engineering framework; and firefighter safety and policy.

Programs of Study

The Department of Fire Protection Engineering serves as a crossroads for bringing together talents from many disciplines to focus on fire and explosion safety problems. The department features formal degree and certificate programs in fire protection engineering, continuing education for the practitioner, and research to uncover new knowledge about fire behavior and fire protection methods.

The fire protection engineering program at WPI adapts previous educational and employment experiences into a cohesive Plan of Study. Consequently, the program is designed to be flexible enough to meet specific and varying student educational objectives. Students can select combinations of major courses, non-major courses, thesis and project topics that will prepare them to proceed in the career directions they desire. The curriculum can be tailored to enhance knowledge and skill in the general practice of fire protection engineering, in fire protection engineering specialties (such as industrial, chemical, energy, design, or testing), or in the more theoretical and research-oriented sphere.

Practicing engineers or others already employed and wishing to advance their technical skills may enter the program as part-time students or take off-campus courses via WPI's Quality Online Courses (see page 10) The master's degree may be completed on a part-time basis in less than two years, depending on the number of courses taken each semester.

WPI offers both master's and doctoral degrees as well as the advanced certificate and graduate certificate in fire protection engineering.

WPI offers combined B.S./M.S. programs for students wishing to complete two degrees in a condensed time frame.

Graduate Certificate

The graduate certificate program in Fire Protection Engineering provides qualified students with an opportunity to further their studies in an advanced field. A completed undergraduate degree in engineering or physical science is the preferred prerequisite for admission. Four courses are selected from a range of offerings in consultation with an academic advisor. Taken together, the courses form a cohesive theme. Options include but are not limited to: Core Concepts in Fire Protection Engineering, Industrial Applications, Hazard and Risk Assessment, Facility and Building Design, Advanced Protection Systems, and Fire Protection Management.

Combined B.S./Master's Program

High school seniors and engineering students in their first three years can apply for this five-year program. This gives high school graduates and others the opportunity to complete the undergraduate degree in a selected field of engineering and the master's degree in fire protection engineering in five years. Holders of bachelor of science degrees in the traditional engineering fields and the master's degree in fire protection engineering enjoy extremely good versatility in the job market.

Master's Program

The M.S. program is a graduate level program in Fire Protection Engineering and Policy that is structured to be equally effective for full-time or part-time distance learning study. The M.S. program is a high level graduate program designed to refine critical thinking skills necessary for making you an industry leader.

Ph.D. Program

The Ph.D. degree in the department of Fire Protection Engineering will focus on a program that produces scholars capable of creating new knowledge for the field. Our Ph.D. graduates will function at a high level no matter where they work or go in the profession.

Admission Requirements

High school graduates applying for the Combined B.S./Master's Program must meet normal undergraduate admission criteria and submit a two-page essay articulating their interest in the field. Applicants for the master's or certificate programs should have a B.S. in engineering, engineering technology or the physical sciences. Applicants with no FPE work experience should submit a two-page essay articulating their interest in the field.

Students with science degrees and graduates of some engineering technology disciplines may be required to take selected undergraduate courses to round out their backgrounds.

GRE scores are required for all international students and all Ph.D. applicants.

Degree Requirements

For the M.S.

The program for a master of science in fire protection engineering is flexible and can be tailored to individual student career goals. The fire protection engineering master's degree requires 30 semester hours of credit. Both a thesis and non-thesis option are offered. A 9 credit thesis can replace 9 credits of course work. All M.S. students are required to take 9 units of core classes; FP 521, FP 570, FP 553, and at least one Fire Protection Integration course; FP 571 and/or FP 573. The remaining credits 18 credits are chosen by the student and up to 9 credits can be taken outside of the Fire Protection discipline (with academic advisors approval).

For the Ph.D.

The degree of doctor of philosophy is conferred on candidates in recognition of high scientific attainments and the ability to conduct original research. Ph.D. students must complete a minimum of 90 semester hours of graduate work after the bachelor's degree (or 60 semester hours after the master's). This includes at least 15 semester hours of fire protection engineering course credits and 30 hours of dissertation research.

Doctoral students must successfully complete the fire protection engineering qualifying examination, a research proposal and public seminar, and the dissertation defense.

Graduate Internships

A unique internship program is available to fire protection engineering students, allowing them to gain important clinical experiences in practical engineering and research environments. Students are able to earn income while maintaining their student status. Internships are generally full time for one year and provide the student a chance to try out various areas of practice, generate income, gain knowledge and experience, and make valuable lifetime contacts.

Research Laboratories

Fire Science Laboratory

This brand new and exciting laboratory facility supports both fundamental studies and large scale engineering studies, experimentation in fire dynamics, combustion/explosion phenomena, detection, and fire and explosion suppression. The Fire Propagation Apparatus, cone calorimeter, infrared imaging system, phase doppler particle analyzer and room calorimeter are also available, with associated gas analysis and data acquisition systems, making this a truly unique awe-inspiring place to conduct research.

The wet lab area supports water-based fire suppression and demonstration projects.

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Serving as both a teaching and research facility, the lab accommodates undergraduate projects as well as graduate students in fire protection engineering, mechanical engineering and related disciplines.

Fire Modeling Laboratory

The Fire Modeling Laboratory specializes in computer applications to fire protection engineering and research. Research activities include computational fluid dynamics modeling of building and vehicle fires, flame spread model development, and building egress modeling.

Combustion Laboratory

The WPI Combusion Lab supports studies of fundamental combustion properties as they relate to fire safety. Experimental set-ups are available for the study of self-heating of coal dust; flammable properties of gasoline containers; cross-correlation velocimetry and the laminar burning velocity of flammable dusts.

Course Descriptions

All courses are 3 credits unless otherwise noted.

FP 520. Fire Modeling

Modeling of compartment fire behavior is studied through the use and application of two types of models: zone and field. The zone model studied is CFAST. The field model studied is FDS. Focus on in-depth understanding of each of these models is the primary objective in terms of needed input, equations solved, interpretation of output and limitations. Additional fundamental understanding of fire models is gained via a student developed model. A working student model is required for successful completion of the course. Basic computational ability is assumed. Basic numerical methods are used and can be learned during the course via independent study. (Prerequisite: FP 521 or permission of the instructor.)

FP 521. Fire Dynamics I

This course introduces students to fundamentals of fire and combustion and is intended to serve as the first exposure to fire dynamics phenomena. The course includes fundamental topics in fire and combustion such as thermodynamics of combustion, fire chemistry, premixed and diffusion flames, solid burning, ignition, plumes, heat release rate curves, and flame spread. These topics are then used to develop the basis for introducing compartment fire behavior, pre- and post-flashover conditions and zone modeling. Basic computational ability is assumed. Basic numerical methods are used and can be learned during the course via independent study. (Prerequisites: Undergraduate chemistry, thermodynamics or physical chemistry, fluid mechanics and heat transfer.)

FP 553. Fire Protection Systems

This course provides an introduction to automatically activated fire suppression and detection systems. A general overview is presented of relevant physical and chemical phenomena, and commonly used hardware in automatic sprinkler, gaseous agent, foam and dry chemical systems. Typical contemporary installations and current installation and approval standards are reviewed. (Prerequisites: Undergraduate courses in chemistry, fluid mechanics and either thermodynamics or physical chemistry.)

FP 554. Advanced Fire Suppression

Advanced topics in suppression systems analysis and design are discussed with an aim toward developing a performance-based understanding of suppression technology. Automatic sprinkler systems are covered from the standpoint of predicting actuation times, reviewing numerical methods for hydraulic analyses of pipe flow networks and understanding the phenomenology involved in water spray suppression. Special suppression systems are covered from the standpoint of two-phase and non-Newtonian pipe flow and simulations of suppression agent discharge and mixing in an enclosure. (Prerequisite: FP 553 or special permission of instructor.)

FP 555. Detection, Alarm and Smoke Control

Principles of fire detection using flame, heat and smoke detector technology are described. Fire alarm technology and the electrical interface with fire/smoke detectors are reviewed in the context of contemporary equipment and installation standards. Smoke control systems based on buoyancy and HVAC principles are studied in the context of building smoke control for survivability and safe egress. (Prerequisites: FP 553 and FP 521, which can be taken concurrently.)

FP 570. Building Fire Safety I

This course focuses on the presentation of qualitative and quantitative means for firesafety analysis in buildings. Fire test methods, fire and building codes and standards of practice are reviewed in the context of a systematic review of firesafety in proposed and existing structures.

FP 571. Performance-Based Design

This course covers practical applications of fire protection engineering principles to the design of buildings. Both compartmented and non-compartmented buildings will be designed for criteria of life safety, property protection, continuity of operations, operational management and cost. Modern analytical tools as well as traditional codes and standards are utilized. Interaction with architects and code officials, and an awareness of other factors in the building design process are incorporated through design exercises and a design studio. (Prerequisites: FP 553, FP 521 and FP 570, or special permission of the instructor.)

FP 572. Failure Analysis

Development of fire investigation and reconstruction as a basis for evaluating and improving fire-safety design. Accident investigation theory and failure analysis techniques such as fault trees and event sequences are presented. Fire dynamics and computer modeling are applied to assess possible fire scenarios and the effectiveness of fire protection measures. The product liability aspects of failure analysis are presented. Topics include products liability law, use of standard test methods, warnings and safe product design. Application of course materials is developed through projects involving actual case studies. (Prerequisite: FP 521, FP 553, FP 570 or special permission of the instructor.)

FP 573. Industrial Fire Protection

Principles of fire dynamics, heat transfer and thermodynamics are combined with a general knowledge of automatic detection and suppression systems to analyze fire protection requirements for generic industrial hazards. Topics covered include safe separation distances, plant layout, hazard isolation, smoke control, warehouse storage, and flammable liquid processing and storage. Historic industrial fires influencing current practice on these topics are also discussed. (Prerequisites: FP 553, FP 521 or special permission of the instructor.)

FP 575. Explosion Protection

Principles of combustion explosions are taught along with explosion hazard and protection applications. Topics include a review of flammability limit concentrations for flammable gases and dusts; thermochemical equilibrium calculations of adiabatic closed-vessel deflagration pressures, and detonation pressures and velocities; pressure development as a function of time for closed vessels and vented enclosures; the current status of explosion suppression technology; and vapor cloud explosion hazards.

FP 580. Special Problems

Individual or group studies on any topic relating to fire protection may be selected by the student and approved by the faculty member who supervises the work. Examples include:

- Business Practice
- Combustion
- People in Fires
- Fire Risk and Regulatory Policy
- Fire Dynamics II
- Fire and Materials
- Forensic Techniques
- Uncertainty in FPE Design and Decision Making

FP 587. Fire Science Laboratory

This course provides overall instruction and hands-on experience with fire-science-related experimental measurement techniques. The objective is to expose students to laboratory-scale fire experiments, standard fire tests and state-of-the-art measurement techniques. The lateral ignition and flame transport (LIFT) apparatus, state-of-the-art smoke detection systems, closed-cup flashpoint tests and gas analyzers are among the existing laboratory apparatus. Fire-related measurement techniques for temperature, pressure, flow and veloci ty, gas species and heat fluxes, infrared thermometry, laser doppler velocimetry (LDV) and laser-induced fluorescence (LIF) will be reviewed. (Prerequisite: FP 521.)

FP 590. Thesis

Research study at the M.S. level.

FP 690. Ph.D. Dissertation

Interactive Media & Game Development

Faculty

A. R. Agloro, Assistant Professor; Ph.D., University of Southern California, 2015. Participatory and community-based game design, activist media making, critical race and ethnic studies, speculative fiction and futurism.

E. O. Agu, Associate Professor; Ph.D., University of Massachusetts, 2001. Computer graphics, wireless networking, and mobile computing.

I. Arroyo, Assistant Professor; Ed.D., M.S., University of Massachusetts, Amherst, 2003. Learning with novel technologies; multimedia learning; intelligent tutoring systems; wearable learning and e-Textiles; learner characteristics and their relationship to learning; connection between affect and learning; educational data mining and student modeling.

F. W. Bianchi, Professor; D.A., Ball State University. Virtual orchestra, multichannel sound design.

M. L. Claypool, Professor; Ph.D., University of Minnesota, 1997. Distributed systems, networking, multimedia and online games.

J. deWinter, Associate Professor; Ph.D., University of Arizona, 2008. New media theory and praxis, spatial and visual rhetorics, histories and theories of rhetoric, post-colonial theory, Japanese rhetoric and culture.

J. L. Forgeng, Adjunct Associate Professor; Ph.D., University of Toronto, 1991. Medieval and Renaissance history, global history, history of technology, arms and armor.

L. Harrison, Assistant Professor, Ph.D., University of North Carolina at Charlotte, 2013. Data visualization, human-computer interaction.

N. T. Heffernan, Associate Professor; Ph.D., Carnegie Mellon University, 2001. Educational data mining, learning sciences and technology.

B. J. Moriarty, Professor of Practice; M.Ed., Framingham State University, 2014. Digital games and culture, virtual communities, interactive fiction.

D. M. O'Donnell, Teaching Professor; M.F.A., Brandeis University. Game and level design, narrative, and the impact of new media on society.

E. Ottmar, Assistant Professor, Ph.D., University of Virginia, 2011. Theories in developmental, educational, and cognitive psychology, and mathematics and teacher education.

G. D. J. Phillies, Professor; D.Sc., Massachusetts Institute of Technology. Tabletop strategy games, light-scattering spectroscopy, complex fluids, statistical mechanics, biophysical chemistry, polymer dynamics, surfactants, wavelets.

C. Rich, Professor; Ph.D., Massachusetts Institute of Technology, 1980. Artificial intelligence and its intersections with human-computer interaction, interactive media & game development, robotics, intelligent tutoring systems, knowledge-based software tools.

J. Rosenstock, Associate Professor; M.F.A., School of the Art Institute of Chicago, 2004. Multimedia performance, interactive installation art, experimental electronic instrument design, diasporic music and culture, video/music hybrids, and stencil art.

L. Sheldon, Professor of Practice; M.F.A. California Institute of the Arts, 1974. Game writing, design and production, level design, applied (serious) games.

J. Sonbonmatsu, Associate Professor; Ph.D., University of California Santa Cruz. Continental philosophy, Marxism, sociology, critical animal studies, feminist theory.

R. P. H. Sutter, Instructor/Lecturer; B.S., New England Institute of Art, 2010. 3D animation, digital sculpting/character creation, games, augmented reality, traditional animation and art.

K. Zizza, Adjunct Instructor; Digital audio, game design.

A full listing can be found here: http://imgd.wpi.edu/faculty.html

Program of Study

The Master of Science in Interactive Media & Game Development (IMGD) is designed for those interested in the design of immersive, interactive environments. The intended audience includes college graduates looking for continued education in interactive media, game-industry professionals looking to assume leadership roles, professionals from other fields retooling for the game industry, and those seeking scholarship in interactive media. Graduate students in IMGD: 1) take core courses that provide a base of knowledge relevant to the design of interactive media; 2) select courses from Technical, Serious Games, or Management Focus areas that enable tailoring the degree to suit interests and career goals; and 3) design, develop, and evaluate a substantial group project and/or undertake a thesis with novel scholarship as a capstone experience. Graduates with an IMGD graduate degree will be qualified to pursue a diverse range of careers in the interactive media, computer games, or related industries, becoming producers, designers, academics, or project leaders in specific subfields such as technology, art, or design.

Admission Requirements

- Statement of purpose that details:
  - the student's goals, and
  - the student's previous industry or academic experiences.
- Proof of a four-year degree. Applicants who are not participating in the B.S./M.S. program must submit a final transcript showing that they have completed a bachelor's degree or its equivalent before enrolling in the M.S. program.
- Three letters of recommendation from individuals who can comment on the student's qualification for pursuing graduate study in IMGD.
- Applicants may submit other material supporting their application, such as a portfolio of their work.

More information on admissions can be found here: http://imgd.wpi.edu/gradadmin-requirements.html

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Degree Requirements

IMGD M.S. students undertake a Game Design Studio course (3 credit hours), a set of core courses (9 credit hours) covering various aspects of design, supplemented by two courses (6 credit hours) supporting a focus area (Serious Games, Technical, or Management), and one elective course (3 credit hours). Each student is required to complete either a Master's thesis (a systematic approach to addressing an identified research question, typically done individually) or a Master's project (a substantial development effort that follows a production plan to implement a design vision, typically done in teams) to complete the degree requirements (9 credit hours).

Game Design Studio (3 credits)

IMGD 5000. Game Design Studio

Core Courses
Choose 3 of 4 (9 credits)

IMGD 5100. Immersive Human-Computer Interaction

IMGD 5200. History and Future of Immersive and Interactive Media

IMGD 5300. Design of Interactive Experiences

IMGD 5400. Production Management for Interactive Media

Focus Courses (6 credits)

Technical Focus, or

Serious Games Focus, or

Management Focus

(see details at http://imgd.wpi.edu/gradrequirements.html)

Elective Course (3 credits)

Selected from the courses in the Core and Focus areas, or

IMGD 5099 (Special Topics in IMGD).

Thesis/Project (9 credits)

The IMGD program also offers a B.S./M.S. program for current IMGD undergraduate students. Students enrolled in this program may count up to 12 credit hours of specific undergraduate courses towards both their B.S. and M.S. degrees.

Details on the degree requirements for both M.S. and B.S./M.S. students can be found here: http://imgd.wpi.edu/gradrequirements.html

Facilities/Research Labs /Research Centers

- IMGD Lab. 27-seat teaching/research lab.
- Zoo Lab. 25-seat teaching/research lab.
- Digital Art Studio. Work space for both digital and traditional art.
- Human Interaction in Virtual Environments (HIVE) Lab). Research lab for designing effective interfaces for virtual reality and games.
- Human-Robot Interaction (HRI) Lab. Research lab for improving face-to-face interaction between robots and humans.
- Performance Evaluation of Distributed Systems (PEDS) Lab. Design and analysis of distributed systems, with a special focus on the performance on networking.
- Grad Innovation Studio. Collaborative design work space.
- Image Science Research Group (ISRG). Conducts interdisciplinary research into the theory and application of graphics, visualization, image processing and computer vision techniques.

Course Descriptions

All courses are 3 credits unless otherwise noted.

IMGD 5000. Game Design Studio

This is a "studio" course in which the instructor will guide and mentor the students on individual and/or joint projects. The focus of the course will be on the design of interactive media and games, with the students designing (and optionally implementing) one or more games or interactive experiences. There will also be readings and discussion of design theory as it relates to student projects. This course can be taken for M.S. credit twice if desired.

IMGD 5100. Immersive Human-Computer Interaction

Immersive environments are those which give the user the feeling of occupying a space different from their current physical space. They are created in the mind of the user by careful selection of sensory stimuli and support for natural interaction. This course focuses on the design and evaluation of user interfaces that support user immersion in several contexts, including desktop, head-mounted display, large-screen, and mobile situations. Through a combination of traditional lecture, literature review, and hands-on work, students will learn to critically evaluate different alternatives, build prototype systems, and design comparative evaluations to test the effectiveness of various techniques. Students will be expected to implement several techniques as part of this course. (Prerequisites: A demonstrated proficiency to program. A course on traditional human-computer interaction is recommended.)

IMGD 5200. History and Future of Immersive and Interactive Media

This course will familiarize students with the history of the development, deployment, commercialization, and evolution of immersive and active media. The lesson plan will cover a broad range of enabling technologies, such as geometric perspective drawing, pre-20th-century panoramic displays, photography and the stereoscope, sound recording and reproduction, motion pictures, radio and television, the planetarium, immersive and 3-dimensional cinema, and special attraction venues, with a particular focus on digital games. Current trends and future directions will also be considered. Students will attend seminars and lectures, read and discuss texts on media history and aesthetics, and write an original research paper. Midterm and final exams test students' knowledge and understanding of important events and developments. A student may not receive credit for both IMGD 5200 and IMGD 4200. (Prerequisites: An understanding of dominant themes and genres in video games)

IMGD 5300. Design of Interactive Experiences

This course will introduce students to the theories of design, the purpose of which is to guide students in articulating a design vision that can then be implemented in an interactive experience such as a computer game or an art installation. The design elements addressed in this course are as follows: narrative, visual, sound, spatial, challenges and objectives, and characters. This course also emphasizes the communicative strategies needed to sell other people on a design in order to enter production, convince investors, and engage users. Students will be required to design an environment that is populated in a meaningful way that is dependant on the purpose of their visions. They will provide mock-ups of this environment that they must present to their stakeholders - the professor and peers - and finally create prototypes that help them sell their design idea. Throughout the class, students will be writing their designs in professional genres, presenting their designs to the class (often called a pitch), and discuss the theories and practices of design during in-class meetings. (Prerequisites: A course on game design, or equivalent work experience)

IMGD 5400. Production Management for Interactive Media

This course focuses on the process of creating a set of documents encompassing the design and vision of a piece of interactive media, methods for structuring the implementation of the design, and tools for successfully managing the project. Students will analyze different types of design documents, focusing on form and purpose while also considering audience and publication medium. Students will write design documents, give peer feedback, and revise their own documents based on feedback received. In order to see their design transform from document to product, students will study different project management methods and employ them, defining in detail discrete components, timelines, milestones, players and their responsibilities, and status reports to stakeholders. Tools common to managing interactive media projects (e.g., source-code revision control, asset management, scheduling) will be used throughout the process. (Prerequisites: Experience working on development projects)

Interdisciplinary Programs

New fields of research and study that combine traditional fields in innovative ways are constantly evolving. In response to this, WPI encourages the formation of interdisciplinary graduate programs to meet new professional needs or the special interests of particular students.

Interdisciplinary Ph.D. Programs

Interdisciplinary Ph.D. programs are initiated by groups of at least three full-time faculty members who share a common interest in a cross-disciplinary field. A sponsoring group submits to the Committee on Graduate Studies and Research (CGSR) a proposal for an interdisciplinary degree, together with all the details of the degree requirements and the credentials of the members of the sponsoring group. At least one member of the group must be from a department or program currently authorized to award the doctorate.

If the CGSR approves the proposal, the sponsoring group serves in place of a department in the administration of the approved interdisciplinary program. Administrative duties include admitting and advising students, preparing and conducting examinations, and certifying the fulfillment of degree requirements.

WPI currently offers the Interdisciplinary Ph.D. in Learning Sciences and Technologies (see page 114), and Systems Modeling (see page 167).

Students may also design their own interdisciplinary Ph.D. program in consultation with faculty members relevant to the proposed project.

In addition to the general requirements established by WPI for an interdisciplinary doctoral degree, applicants must pass a qualifying examination. This examination will test the basic knowledge and understanding of the student in the disciplines covered by the research as is normally expected of degree holders in the disciplines. It must be administered within the first 18 credits of registration in the interdisciplinary Ph.D. program. The examination will be administered by a committee of no less than three members, approved by CGSR, representing the disciplines covered by the research. Students are allowed at most two attempts at passing the examination, and may take a maximum of 18 credits prior to passage.

Interdisciplinary Master's Programs

Interdisciplinary master's programs require at least 30 credits beyond the bachelor's degree. They may also include a thesis or project requirement. Proposals for such programs are initiated by groups of at least two faculty members from different academic departments who share a common interest in a cross-disciplinary field. The sponsoring group submits a proposal for an interdisciplinary degree to the Committee on Graduate Studies & Research (CGSR) that includes the details of a program of study and the credentials of the members of the group. At least one member of the group must be from a department or program currently authorized to award the masters degree. No more than half of the total academic credit may be taken in any one department. The CGSR may request additional input from the sponsors or appropriate departments. If the CGSR approves the proposal, the sponsoring group serves in place of a department in administration of the approved program.

Current Interdisciplinary Master's degree programs include Systems Modeling, Construction Project Management, Impact Engineering, Manufacturing Engineering Management, Power Systems Management, Systems Engineering. and Materials Systems Engineering.

Bioscience Administration

Faculty

Faculty hold a full time position in a WPI academic department or are adjunct faculty vetted by a WPI academic department head.

Program of Study

WPI offers graduate levels studies in the field of Bioscience Administration leading to the Master of Science. This program is designed to offer both business and science education thus meeting an educational need in the life sciences and bioresearch fields. This degree is applicable for students seeking employment in pharmaceutical, biotechnology, and biomedical device companies. This program helps science professionals advance their science knowledgebase and also helps them build the necessary administrative infrastructure for their field.

Admissions Requirements

Admission for the Master's degree is consistent with the admission requirements listed in the Graduate Catalog for a Master of Science degree. Appropriate undergraduate bachelor's degree majors include but are not limited to life science, management, engineering, and computer science. Students with other backgrounds may be considered with the approval of the program administrator. Students need a working knowledge of basic biotechnology, biochemistry, cell biology, and chemistry.

Certificates

Graduate Certificate in Bioscience Management

This certificate program is proposed to meet the needs of a variety of corporations and individuals who are taking a first step toward an M.S. in Bioscience Administration. The framework presents minimum requirements for the distribution of bio/life-science and management courses, but provides flexibility. This certificate is composed of at least 17 credits of graduate coursework. Refer to the web for more information http://www.wpi.edu/offices/cpe.html.

Degree Requirements

Interdisciplinary Master of Science in Bioscience Administration

Admission

All applicants for this program must hold a bachelor's degree from an accredited college or university recognized by WPI. Acceptable bachelor's degrees include life science, management, engineering, and computer science. Students with other backgrounds may be considered with the approval of the program administrator. GRE and GMAT examinations are not required for admission to the program.

Requirements

Awarding of the degree requires successful completion of at least 30 credit hours of graduate coursework, not to exceed 14 credit hours in Biomedical engineering, within the Bioengineering or Custom Science tracks, and no more than 12 credit hours from any other discipline, including required or elective courses or directed research credits.

Curriculum

The Master of Science in Bioscience Administration consists of three track options: Life Science, Bioengineering, and Custom Science. Although the courses are not specified in any of the tracks, the number of credit hours completed must conform to the breakdown found Table I.

Each student must have a Plan of Study approved by the program administrator within their first 9 credits.

Table I: Three track options for the Master of Science in Bioscience Administration

Life Science Track:

6-12 Credit Hours in Chemistry/ Biochemistry

6-12 Credit Hours in Management

6-12 Credit Hours in Biology/Biotechnology

3-9 Credit Hours of electives or directed research

Bioengineering Track:

9-14 Credit Hours in Biomedical Engineering

6-12 Credit Hours in Management

3-12 Credit Hours in Chemistry or Biology

3-9 Credit Hours of electives or directed research

Custom Science Track:

16-24 Credit Hours selected from Biomedical Engineering, Biology/Biotechnology, Chemistry/Biochemistry, Computer Science, Mathematical Science

6-12 Credit Hours in Management

Transfer Credits

Consistent with WPI policy in most graduate areas, up to one-third of the degree program (10 credit hours) may be transferred from an accredited college or university with approval of the program administrator.

Manufacturing Engineering Management

Faculty

Faculty hold a full time position in a WPI academic department or are adjunct faculty vetted by a WPI academic department head.

Program of Study

- Interdisciplinary Master of Science in Manufacturing Engineering Management

This program is designed to meet the demand from professionals who typically have an undergraduate degree in engineering, work experience in manufacturing, and a desire to pursue a master's degree curriculum with equal emphasis in both manufacturing engineering and manufacturing/operations management. They project their career as continuing to need a balanced growth in manufacturing engineering and manufacturing management.

Admissions Requirements

Students will be eligible for admission into the program if they have earned an undergraduate degree from an accredited university consistent with the WPI Graduate Catalog. Students should have a bachelor's degree in science or engineering. Students with other backgrounds will be considered based on their interest, formal education and experience in manufacturing. Admission decisions will be made by the sponsoring faculty based on all factors presented in the application, including prior academic performance, quality of professional experience, letters of recommendation, etc.

Degree Requirements

Interdisciplinary Master of Science in Manufacturing Engineering Management

Students must complete 30 credit hours of course work in Manufacturing, Engineering, and Management related courses as defined by the coordinating faculty.

Business (choose 12 credits)

- OBC 500 Group and Interpersonal Dynamics in Complex Organizations
- MIS 500 Innovating with Information Systems
- OBC 531 Managing Organizational Change
- OIE 541 Operations Risk Management
- OIE 544 Supply Chain Analysis and Design
- OIE 546 Managing Technological Innovation
- OIE 548 Productivity Management
- MIS 576 Project Management
- Engineering (choose 15 credits)
- FP 563 Operations Risk Management
- MFE 510 Control and Monitoring of Manufacturing Processes
- MFE 511 Application of Industrial Robotics
- MFE 520 / MTE 520 / ME 543 Design and Analysis of Manufacturing Processes
- MFE 530 / ME544 Computer-Integrated Manufacturing
- MFE 540 Design for Manufacturability
- MFE 598* Directed Research

Power Systems Management

Faculty

Faculty hold a full time position in a WPI academic department or are adjunct faculty vetted by a WPI academic department head.

Programs of Study

- Interdisciplinary Master of Science in Power Systems Management
- Certificate in Power Systems Management

Power Systems Engineering education is in high demand in the United States and more so in developing nations. WPI has broadened its offerings of courses in this area, and now offers a new level of flexibility for students and their current or prospective employers. In addition, the School of Business provides an attractive palette of relevant courses to enhance the professional skills of practicing engineers. This framework has created programs to meet industry demands.

Admissions Requirements

Students will be eligible for admission into the program if they have earned an undergraduate degree from an accredited university consistent with the WPI Graduate Catalog. Normally, an undergraduate bachelor's degree

in electrical engineering, computer engineering, or computer science is expected. Students with other backgrounds may be considered with the approval of the faculty. GRE examinations are required for all international applicants.

Degree Requirements

Interdisciplinary Master of Science in Power Systems Management

At least 30 credit ours composed of:

- At least 12 credits but no more than 15 credits of graduate level coursework in Power Systems Engineering (course prefix ECE with course numbers from 5500 through 5599)
- At least 12 but no more than 14 credits of graduate level coursework in Business (example courses prefixed by BUS, MIS, OBC, OIE, etc.).

Electives:
Under the direction of the advisors, each student will select 6 credits of coursework at the 4000 level (maximum of two) or at the graduate level (designated as 500-, 5000-, or 600-level) in computer science (CS), physics (PH), engineering (BME, CHE, CE, ECE (1 only), FP, MFE, MTE, ME, RBE, and SYS), mathematics (MA), and/or Systems Dynamics (SD) to complete the Interdisciplinary Master of Science degree.

There is no thesis option for this degree.

Certificates

Certificate in Power Systems Management

This certificate program is proposed to meet the needs of a variety of corporations and individuals who are taking a first step toward an M.S. in Power Systems Management. The framework presents minimum requirements for the distribution of power systems and management courses, but provides flexibility for the student.

This certificate must consist of at least 17 credits of graduate coursework.

For more information please consult the WPI web at
http://cpe.wpi.edu/protection.html

Course

IDG 599. Capstone Project Experience in Power Systems Management
This project-based course is an interdisciplinary exercise that integrates the technical aspects of power systems engineering with challenges of meeting business goals within the framework of the corporate organizational structure. It allows the students to apply the skills and knowledge acquired throughout the Power Systems Management curriculum. Students are encouraged to select projects with practical significance to their current and future professional responsibilities. Each project is normally conducted in teams of two to four students. They are administered, advised, and evaluated by WPI faculty as part of the learning experience, but students are also encouraged to seek mentorship from experienced colleagues in the Power Systems profession. (Prerequisites: Since the Capstone Project will draw on knowledge obtained throughout the degree program, it is expected that the student will have completed most or all of the coursework within their plan of study before undertaking the capstone project.)

Other Certificates

The Certificate in College Teaching

Purpose

WPI offers an innovative program, managed by the Colleges of Worcester Consortium, for graduate students wishing to develop skills in college teaching. Many doctoral and even masters' degree holders will devote a least some of their professional time to college-level teaching. The Certificate in College Teaching program offers an opportunity to acquire both teaching skills and professional recognition of high-level preparation to teach.

The Certificate represents a collaborative institutional response to the ever-present challenges of promoting exemplary teaching in today's complex higher education environments. Most college professors are never trained to be teachers. Preparation for the college classroom involves more than a solid base of knowledge in a discipline; it requires a systematic inquiry into the pedagogies and processes that facilitate learning. Our certificate program is grounded in the latest educational research of best practices in college teaching, and is designed to enhance the teaching and learning experiences for faculty and students at our member institutions.

The primary focus of the Certificate is to prepare graduate students and adjunct faculty for a career in academia. Research has shown that graduate students with some formal preparation in college teaching have a substantial advantage in the academic job market. Once hired, the new faculty members are better prepared to assume their teaching duties and are, consequently, more productive in developing their research programs. Similarly, more experienced college faculty can also benefit from such teaching certificate programs, as they may be very well prepared in their disciplines, but desire formal training in pedagogy.

Program

Students may take any combination of the courses offered. Generally students begin with the 2-credit Seminar in College Teaching (IDG 501, description below) which is usually taught fall, spring and summer terms. The full Certificate program is 6 credits, with three 1-credit additional elective courses taken and culminating in the one-credit Capstone Practicum.

Tuition

WPI covers the full cost for graduate students approved by their department head to participate ($299 credit). Adjunct and other faculty teaching at WPI should check with their department heads about departmental policies for supporting the Certificate program. WPI employees may also have tuition benefits that will cover the cost of Certificate courses; contact Human Resources for details. The program is open to all qualified persons wishing to participate at their own expense.

Information

Courses are taught at various Consortium sites, with WPI and Clark continuing to be the most common hosts. For information on specific course descriptions and availability, see the Consortium website at http://www.heccma.org.

Questions

Contact Chrysanthe Demetry, Ph.D.
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WPI, 100 Institute Rd
Worcester, MA 01609 USA
Email: cdemetry@wpi.edu
Tel: (508)831-5195; Fax: (508)831-5178

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Course

IDG 501. Seminar in College Teaching
(2 credits)

This seminar is designed to acquaint graduate students with some of the basic principles and theories of education and with instructional practices associated with effective college teaching. This information applies without regard to the particular nature of the subject matter being taught; the emphasis is on the educational process, not the disciplinary content. Course activities include readings, lectures, discussion, and individual and group projects. Topics covered include an introduction to learning theories, cognitive development and motivation for learning; effective teaching skills such as lecturing, class discussion, active and cooperative learning, and use of instructional technology; evaluating student performance; and life as a college professor. Students who have completed IDG 501 will be prepared for ISG 502 Practicum in College Teaching, which is offered as an independent study on demand. *This course will be offered at a host university (TBD), with credit transferred to WPI.*

Certificate in Nuclear Science and Engineering

Faculty

The faculty hold a full time position in a WPI academic department or are adjunct faculty approved by an academic department and the NSE program review committee.

Program of Study and Certificate Requirements

The graduate certificate in nuclear science and engineering will require the successful completion of 12 graduate credits with an overall GPA of 3.00. The courses will be selected from the list below.

All students must successfully complete four of the five courses listed below:

- NSE 510 Introduction to Nuclear Science and Engineering (3 credits)
- NSE 520 Applied Nuclear Physics (3 credits)
- NSE 530 Health Physics (3 credits)
- NSE 540 Nuclear Materials (3 credits)
- NSE 550 Reactor Design and Operations (3 credits)

Admissions Requirements

Admission to the Nuclear Science and Engineering graduate certificate program is consistent with the admissions requirements listed in this catalog for graduate certificates. Appropriate undergraduate degree majors include all engineering and science majors.

Course Descriptions

NSE510. Introduction to Nuclear Science and Engineering
(3 credits) (offered annually)

This introductory course provides an overview of the field of nuclear science and engineering as it relates to nuclear power and nuclear technologies. Fundamental concepts relevant to nuclear systems are introduced, including radioactivity, radiation interaction phenomena, chain reaction physics, and transport in engineering materials. Nuclear reactor physics and design concepts are introduced with focus on light water fission reactors. A survey of advanced nuclear technologies and applications is provided. Prerequisites: graduate or senior standing or consent of the instructor.

NSE 520. Applied Nuclear Physics
(3 credits) (offered annually)

This course introduces engineering and science students to the fundamental topics of nuclear physics for applications, basic properties of the nucleus, nuclear radiations, and radiation interactions with matter. The course is divided into four main sections: (1) introduction to elementary quantum mechanics, (2) nuclear and atomic structure, (3) nuclear decays and radiation, and (4) nuclear matter interactions and nuclear reactions. Prerequisites: Physics of mechanics and electrodynamics (PH 1110/11 and PH 1120/21) and mathematical techniques up to and including ordinary differential equations (MA 2051)

NSE 530. Health Physics
(3 credit) (offered biennially)

This course builds on fundamental concepts introduced in NSE 510 and applies them to key topics in health physics and radiation protection. Health physics topics include man-made and natural sources of radiation, dose, radiation biology, radiation measurement, and radiation safeguards. Radiation protection concepts are explored as they apply to existing and advanced nuclear power generators, including reactor safety, nuclear waste and byproducts, regulatory constraints, and accident case studies. Prerequisites: graduate standing or consent of the instructor

NSE 540. Nuclear Materials
(3 credits) (offered biennially)

This course applies fundamental materials science concepts to effects on materials in harsh nuclear environments. An overview is provided on environments, special nuclear materials, and constraints in materials selection. Relationships are developed between nuclear effects on crystal structure, microstructure, degraded material performance, and bulk properties of engineering and electronic materials. Case studies provide examples of enhancements induced my multiple harsh environments and mitigation through material design hardening. Prerequisites: ES 2001 or equivalent.

NSE 550. Reactor Design, Operations, and Safety
(3 credits) (offered biennially)

This course provides a systems engineering view of commercial nuclear power plant technology. Power plant designs and their evolutions are studied, ranging from early to modern generation light water reactors, as well as advanced designs families, such alternate moderator and breeder reactors. Critical aspects of conventional power reactor designs are explored in detail, including steam supply, reactor core, control, and protection systems. Plant operational characteristics are studied, including reactor dynamics, control, feedback, and fuel cycle management. Critical power plant safety aspects of the design and operations are explored and reinforced with lessons learned from major power generator accidents scenarios (including Three Mile Island, Chernobyl, and Fukushima Daiichi). Prerequisites: graduate standing or consent of the instructor

NSE 595. Special Topics
(1-3 credits)

Arranged by faculty affiliate to the Nuclear Science and Engineering program for individual or groups of students, these courses survey areas that are not covered by the regular NSE course offerings. Exact course descriptions are disseminated by the NSE Program Committee well in advance of the offering. (Prerequisite: Consent of instructor.)

Learning Sciences and Technologies

Faculty

Learning Sciences & Technologies Core Faculty

N. T. Heffernan, Professor and Director; Ph.D., Carnegie Mellon University; Intelligent tutoring agents, artificial intelligence, cognitive modeling, machine learning

I. Arroyo, Assistant Professor; Ed.D., M.S., University of Massachusetts, Amherst; learning with novel technologies; multimedia learning; intelligent tutoring systems; wearable learning and e-Textiles; learner characteristics and their relationship to learning; connection between affect and learning; educational data mining and student modeling.

R. Baker, Assistant Professor; Ph.D., Carnegie Mellon University; educational data mining, learner-computer interaction, gaming the system, student modeling, intelligent tutoring systems, educational games.

J. E. Beck, Assistant Professor; Ph.D., University of Massachusetts, Amherst; educational data mining, student modeling, Bayesian Networks, student individual differences

S. Djamasbi, Associate Professor; Ph.D., University of Hawaii at Manoa; Usability, decision science.

L. Harrison, Assistant Professor; Ph.D., University of North Carolina at Charlotte; Information visualization, visual analytics, human-computer interaction.

E. Ottmar, Assistant Professor; Ph. D., University of Virginia; mathematics teaching and learning; mathematics development and cognition; interventions in schools; instructional quality; social and emotional learning; motivation and engagement; perceptual leaning; teacher/child interactions; observational measurement development

G. B. Somasse, Assistant Teaching Professor; Ph.D., Clark University; Development economics, applied econometrics, policy evaluation, public policy.

J. R. Whitehill, Assistant Professor; Ph.D., University of California, San Diego; Machine learning, crowdsourcing, automated teaching, human behavior recognition.

J. Zou, Assistant Professor; Ph.D., University of Connecticut; Financial time series (especially high frequency financial data), spatial statistics, biosurveillance, high dimensional statistical inference, Bayesian statistics.

Learning Sciences & Technologies Associated Faculty

D. C. Brown, Professor; Ph.D., Ohio State University; Knowledge-based design systems, artificial intelligence

J. K. Doyle, Associate Professor; Ph.D., University of Colorado/Boulder; judgement and decision making, mental models of dynamic systems, evaluation of interventions

K. Fisler, Associate Professor; Ph.D., Indiana University; Interplay of human reasoning and formal logic in the context of hardware and software systems; current projects explore access-control policies and diagrams.

G. T. Heineman, Associate Professor; Ph.D., Columbia University; Component-based software engineering, formal approaches to compositional design

A. C. Heinricher, Professor; Ph.D., Carnegie Mellon University; applied probability, stochastic processes and optimal control theory

C. Rich, Professor; Ph.D., Massachusetts Institute of Technology; Artificial intelligence and its intersections with human-computer interaction, interactive media & game development, robotics, intelligent tutoring systems, knowledge-based software tools

C. Ruiz, Associate Professor; Ph.D., University of Maryland; Data mining, knowledge discovery in databases, machine learning

J. L. Skorinko, Assistant Professor; Ph.D., University of Virginia; soc ial environmental cues, stigmas and stereotyping, perceptions of others

Program of Study

The Learning Sciences and Technologies (LS&T) program offers graduate studies toward the M.S. and Ph.D. degrees. Our state-of-the-art facilities, faculty and strong relationships with K-12 schools provide students with the resources to perform innovative scientific research at the highest level. The diverse learning environment that characterizes our program promotes easy exchange of ideas, access to all the necessary resources, and encourages creative solutions to pressing scientific questions. The LS&T program is based on three affiliated areas – Computer Science, Cognitive and Educational Psychology, and Statistics – and provides opportunities for advanced course work and research for highly qualified students.

Admissions Requirements

Applicants must apply directly to the LS&T program. In order to be capable of performing graduate level work, applicants should have background in at least one of the core disciplines of LS&T, namely, Cognitive/Educational Psychology, Computer Science, or Statistics. We will also consider applicants whose academic background is in Science or Math.

A student may apply to the Ph.D. program in LS&T after completing a bachelor's degree (*in which case a master's degree must first be completed*) or a master's degree in one of the affiliated areas (Computer Science, Cognitive or Educational Psychology or Statistics) or a closely related area. Applicants with other degrees are welcome to apply if they can demonstrate their readiness through other means, such as GRE Subject exams in an affiliated area, or through academic or professional experience. GRE scores are strongly recommended, but not required, for all applicants. Inquiries about the GRE should be made to Dr. Neil Heffernan, the Program Director.

Degree Requirements

For the M.S.

The student may choose between two options to obtain the M.S. degree: thesis or coursework. Students should carefully weigh the pros and cons of these

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alternatives in consultation with their LS&T faculty advisor prior to selecting an option. Completion of the M.S. degree requires 33 graduate credit hours. M.S. LS&T students who wish to become doctoral candidates in LS&T must first complete their M.S. degree in LS&T following the thesis option.

To satisfy the interdisciplinary nature of the LS&T program, each M.S. student must complete the following 15 graduate credit hours that form the core requirements.

- Computer Science Requirement
  [6 graduate credit hours]
  Two LS&T Computer Science courses
- Cognitive Psychology Requirement
  [6 graduate credit hours]
  Two LS&T Cognitive Psychology courses
- Statistics Requirement
  [3 graduate credit hours]
  One LS&T Statistics course; or CS 567. Empirical Methods for Human-Centered Computing

No single graduate course can be double counted to satisfy two of the above requirements.

M.S. in LS&T – Coursework Option

In addition to the 15 graduate credit hours as required by the M.S. core requirements, a student pursuing the coursework option must register for an additional six graduate courses (totaling 18 graduate credit hours). To ensure a sufficient focus on LS&T, two of these courses (for a total of 6 graduate credit hours) must be from the LS&T course list. The remaining four courses (for a total of 12 graduate credit hours) are electives that relate to the student's individual program of study and must be selected in consultation with the student's LS&T advisor.

Note that M.S. graduate credits cannot be from independent study/research courses except by approval of the LS&T Program Director.

M.S. in LS&T – Thesis Option

In addition to the 15 graduate credit hours as required by the M.S. core requirements, a student pursuing the thesis option must satisfactorily complete a written thesis. Any Core or Associated LS&T faculty may serve as the thesis advisor. A thesis consisting of a research or development project worth a minimum of 9 graduate credit hours must be completed and presented to the LS&T faculty. A thesis proposal must be approved by the Core LS&T faculty and the student's advisor before the student can register for more than four thesis credits.

To complete the remaining 9 graduate credit hours, the student must register for an additional three graduate courses. To ensure a sufficient focus on LS&T, two of these courses (for a total of 6 graduate credit hours) must be from the LS&T course list. The remaining course (of 3 graduate credit hours) is an elective that relates to the student's individual program of study and must be selected in consultation with the student's LS&T advisor. As for the coursework option, M.S. graduate credits cannot be from independent study/research courses except by approval of the LS&T Program Director.

No Combined B.S./M.S. Degree

The LS&T program does not offer a combined B.S./M.S. degree.

For the Ph.D.

Students are advised to contact the program director for detailed program guidelines, in addition to the university's requirements for the Ph.D. degree. Students who wish to pursue a Ph.D. in LS&T who completed their M.S. at WPI in LS&T, must have chosen the thesis option.

Fundamentally, it is expected that all LS&T Ph.D. students master the basics of Learning Sciences, apply those concepts to create an innovative technology, and properly analyze their work with the appropriate statistical techniques. Ph.D. students will receive training through a combination of enrolling in courses, satisfying competency requirements and completing a dissertation; all Ph.D. students will be reviewed by the Core LS&T faculty at least once a year to see that they are making satisfactory progress towards these three components of the Ph.D. program.

Course Requirements

The Ph.D. degree in LS&T requires an additional 60 graduate credit hours of work beyond the M.S. degree. Students must take a minimum of 30 graduate credit hours of course work, including independent study, and 30 graduate credit hours of research.

To satisfy the interdisciplinary nature of the LS&T program, each Ph.D. student must complete the following 24 graduate credit hours. To count towards the course requirements, students must get a minimum grade of B for each of the courses. Students receiving a C or below must retake a course in the appropriate area and receive a B or higher.

- Computer Science Requirement
  [9 graduate credit hours]
  Three LS&T Computer Science courses
- Cognitive Psychology Requirement
  [9 graduate credit hours]
  Three LS&T Cognitive Psychology courses
- Statistics Requirement
  [6 graduate credit hours]
  LS&T Statistics courses, or CS 567. Empirical Methods for Human-Centered Computing

All students are required to submit a program of study that describes their planned course work; their LS&T advisor must approve the program. These classes can include graduate classes at WPI, classes at Clark University, particularly from their Psychology Department, and from independent studies. However, to ensure depth in LS&T, no more than 9 credit hours can be from disciplines other than Cognitive Psychology, Computer Science, and Statistics except by the approval of the Program Director.

Students can count previously taken LS&T courses towards these requirements. However, students must still complete 30 graduate credit hours of coursework for the Ph.D. degree. For example, if a student had taken two LS&T Computer Science courses as part of an LS&T M.S. degree, only one more LS&T Computer Science course would be required, but the student would still have to complete 30 graduate credit hours of coursework for the Ph.D. Similarly, students who are transferring in with an M.S. degree will be evaluated for which requirements they have fulfilled, but will still be required to take 30 graduate credit hours of coursework.

To complete the remaining 6 graduate credit hours, the Ph.D. student can register for other graduate courses or independent studies with approval of the student's LS&T advisor.

Competency Requirements

In addition to successful completion of their coursework, Ph.D. students must demonstrate competency in two core areas: Data Analysis and Communication (specifically, Speaking and Writing). Regarding Data Analysis, it is expected that students will learn analysis methods relevant to the Learning Sciences. We have selected these two areas as they are fundamental to success as an empirical scientist and will form the basis of LS&T graduates' future careers.

Competency in both Data Analysis and Communication will be assessed as follows: Students will be expected to conduct a pilot research study towards their graduate research. Students will submit a short paper (10-20 pages) to the Core LS&T faculty who will write a set of questions to be asked during a public presentation by the graduate student of the pilot research project. Possible venues for this include the AIRG (Artificial Intelligence Research Group) or the Learning Sciences Seminar. Students will be graded by at least two Core LS&T faculty on their responses to the LS&T questions, their data analysis, and communication skills at handling spontaneous questions during the talk. This requirement will be handled by the Core LS&T faculty.

Students must complete this competency requirement prior to defending their Ph.D. proposal. Furthermore, competency requirements must be completed within four semesters after students begin as Ph.D. students, except by permission of the Program Director.

Dissertation Requirements

Within six semesters of being admitted to the LS&T Ph.D. program, each student must form a dissertation committee, and write and defend a dissertation proposal. Any deviation from the timetable for the dissertation must be approved by the Program Director. Any Core or Associated LS&T faculty may serve as a research advisor.

A student's dissertation committee is composed of at least four members, as approved by the LS&T Core faculty. The committee must contain at least one Core LS&T faculty member and one faculty member external to WPI. To reinforce the interdisciplinary nature of the degree, at least two of the three cooperating departments (Computer Science, Social Science and Policy Studies and Mathematical Sciences) must have a faculty member on the dissertation committee. The dissertation committee will be responsible for approving the dissertation proposal and final report.

Students must enroll in at least 30 credits for their dissertation. Before presenting and defending their dissertation proposal, students may only enroll in 15 graduate research credit hours. Students are expected to defend their dissertation within six semesters of the acceptance of their dissertation proposal. In addition to the minimum of 30 graduate credit hours of research, the dissertation culminates in the student submitting the document itself and a public defense of the research.

Courses

LS&T Computer Science Courses

- CS 509 Design of Software Systems
- CS 534 Artificial Intelligence
- CS 538 Knowledge Based Systems
- CS 539 Machine Learning
- CS 540 Artificial Intelligence in Design
- CS 546 Human-Computer Interaction
- CS 548 Knowledge Discovery and Data Mining
- CS 565 User Modeling
- CS 566 Graphical Models for Reasoning Under Uncertainty
- CS 567 Empirical Methods for Human-Centered Computing
- CS 568 Artificial Intelligence for Adaptive Educational Technology

LS&T Cognitive Psychology Courses

- PSY 501 Foundations of the Learning Sciences
- PSY 502 Learning Environments in Education
- PSY 503 Research Methods for the Learning Sciences
- PSY 504 Meta-cognition, Motivation, and Affect
- PSY 505 Advanced Methods and Analysis for the Learning and Social Sciences

LS&T Statistics Courses

- MA 511 Applied Statistics for Engineers and Scientists
- MA 540/4631 Probability and Mathematical Statistics I
- MA 541/4632 Probability and Mathematical Statistics II
- MA 542 Regression Analysis
- MA 546 Design and Analysis of Experiments
- MA 547 Design and Analysis of Observational and Sampling Studies
- MA 554 Applied Multivariate Analysis
- MA 556 Applied Bayesian Statistics

Research Labs/Research Groups

Advanced Learning Technologies Research Lab

Prof. Arroyo

We create, explore, and analyze the impact of Learning Technologies for STEM focusing on a variety of important aspects of human learning. Our research spans many areas, including: Personalized Learning, Affect and Motivation, Metacognition, Embodied Cognition and Wearable Devices for Active Learning, Educational Games, Intelligent Pedagogical Agents, Students with Learning Disabilities, Cultural Differences in the design and implementation of Learning Technologies, and Learning Technologies for the Developing World. http://alt.wpi.edu

Educational Data Mining Research Group

Profs. Beck, Heffernan, Whitehill & Arroyo

Large datasets of students' fine-grained interactions (e.g., student S answers math problem X with answer Y at time T) with intelligent tutoring systems, educational interventions, and massive open online courses (MOOCs) enable the exploration and optimization of how learners learn and how teachers teach. By harnessing methods from machine learning -- such as probabilistic graphical models, Markov chains, and deep neural networks -- we can develop more accurate predictors of which and when students will succeed, fail, persist, need help, etc. These predictors can, in turn, serve as the basis for both human-assisted and automated interventions to improve students' learning outcomes and the personalization of learning.

Educational Psychology and Mathematics Learning Lab

Prof. Ottmar

Teaching and learning mathematics is a highly complex social, exploratory, and creative process. We design novel dynamic technologies that make "math come alive" (Graspable Math, From Here to There!) and use eye tracking, mouse gestures, and log files to explore the coordination of attention, cognition, gestures, and strategies when solving mathematical equations. We also use a variety of applied multilevel quantitative methods, observational measures, and assessments to examine the efficacy of instructional, social, and emotional classroom Interventions that can improve K-12 math teaching, learning, and engagement. https://sites.google.com/site/erinottmar/

Embodied Cognition In Mathematics Research Group

Profs. Arroyo & Ottmar

This research group carries out research about new ways of learning, using motor actions as well as cognitive thought. We investigate how children may better learn mathematics while exploring the physical space, getting a different understanding of math learning by gesturing, and using technology to guide them through 3D spaces.

Machine Perception of Human Learning Group

Profs. Whitehill, Heffernan & Beck

This group uses machine learning and computer vision to study how learners learn and how they emote while they learn. Particular interests include the training of deep neural networks to recognize students' facial expressions during learning tasks, and the development of real-time cyberlearning systems that respond instantaneously to learners' current cognitive, affective, and linguistic needs.

Quantitative Methods in the Learning Sciences

Profs. Somasse, Ottmar, Zou & Heffernan

This research group is focus on rigorous quantitative methods such as hierarchical linear models (which is a typical method to use when students are nested inside teachers and teachers are nested inside schools). Other topics include issues that are used a lot in Learning Science like structural question modeling, longitudinal data analysis, propensity score matching, regression discontinuity designs, quasi-experimental designs and advanced topics like principal stratification. The faculty in this group like to apply (and adapt) statistical methodologies to solves the problems they are working on.

Running Classroom Experiments on the Web

Profs. Heffernan, Beck, Ottmar, Arroyo & Whitehill

We use a number of web-based platforms and technologies (i.e. ASSISTments, MathSpring, GraspableMath) to conduct randomized-controlled trials in K-12 mathematics classrooms. These studies help us understand "what works" with regards to different pedagogical techniques, content, feedback, and tasks, and helps us develop a better understanding of the mechanisms guiding learning. Together the group has over 100 randomized controlled trials running each year. There are a set of methodologic issues that their research group tackle related to student-level randomized controlled assignment.
http://www.neilheffernan.net/

Course Descriptions

All courses are 3 credits unless otherwise noted.

PSY/SEME 501. Foundations of the Learning Sciences

This course covers readings that represent the foundation of the learning sciences, including: Foundations (Constructivism, Cognitive Apprenticeship, & Situated Learning); Approaches (Project-based Learning, Model-based reasoning, Cognitive Tutors); and Scaling up educational interventions. The goal of this course is for students to develop an understanding of the foundations and approaches to the Learning Sciences so that they can both critically read current literature, as well as build on it in their own research. (Prerequisites: None)

PSY/SEME 502. Learning Environments in Education

In this class, students will read and review both classic and critical current journal articles about learning technologies developed in the Learning Sciences. This course is designed to educate students on current technological approaches to curricular design, implementation, and research in the Learning Sciences. (Prerequisites: None)

PSY/SEME 503. Research Methods for the Learning Sciences

This course covers research methods used in the Learning Sciences. Students will gain expertise and understanding of think-aloud studies, cognitive task analysis, quantitative and qualitative field observations, log file analysis, psychometric, cognitive, and machine-learning based modeling, the automated administration of measures by computer, and issues of validity, reliability, and statistical inference specific to these methods. Students will learn how and when to apply a variety of methods relevant to formative, performance, and summative assessment in both laboratory and field settings. Readings will be drawn primarily from original source materials (e.g. journal articles and academic book chapters), in combination with relevant textbook chapters. (Prerequisites: SS 2400, Methods, Modeling, and Analysis in Social Science, comparable course, or instructor discretion.)

PSY/SEME 504. Meta-cognition, Motivation, and Affect

This course covers three key types of constructs that significantly impact learning and performance in real-world settings, including but not limited to educational settings. Students will gain understanding of the main theoretical frameworks, and major empirical results, that relate individuals' meta-cognition, motivation, and affect to real-world outcomes, both in educational settings and other areas of life. Students will learn how theories and findings in these domains can be concretely used to improve instruction and performance, and complete final projects that require applying research in these areas to real-world problems. Students will do critical readings on research on this topic. (Prerequisites: None)

PSY 505. Advanced Methods and Analysis for the Learning and Social Sciences

This course covers advanced methods and analysis for the learning and social sciences, focusing on contemporary modeling and inference methods for the types of data generated in these forms of research. This course will enable students to choose, utilize, and make inferences from analytical metrics that are appropriate and/or characteristic to these domains, properly accounting for the characteristic forms of structure found in data typically collected for research in the learning and social sciences. Some of the topics covered will include ROC analysis and the use of A' for assessing student models, learning curve and learning factor analysis, social network and dyad analysis, and appropriate methods for tracking student learning and behavior in longitudinal data. Readings will be drawn from original source materials (e.g. journal articles and academic book chapters). (Prerequisites: PSY503, Research Methods for the Learning Sciences, comparable course, or instructor discretion.)

To see the Computer Science and Math classes, refer to those departments, pages 75 and 130.

Manufacturing Engineering

www.wpi.edu/+mfe

Faculty

R. D. Sisson Jr., George F. Fuller Professor; Director, Manufacturing and Materials Engineering; Ph.D., Purdue University. Materials process modeling, manufacturing engineering, corrosion, and environmental effects on metals and ceramics.

D. Apelian, Howmet Professor of Engineering; Director, Metal Processing Institute; Sc.D., Massachusetts Institute of Technology. Solidification processing, spray casting, molten metal processing, aluminum foundry processing, plasma processing, and knowledge engineering in materials processing.

I. Bar-On, Professor; Ph.D., Hebrew University of Jerusalem. Mechanical behavior of materials, fracture and fatigue of metals, ceramics and composites, reliability and lie prediction, and electronic packaging.

C. A. Brown, Professor, Director Surface Metrology Laboratory; Ph.D., University of Vermont, 1983. Surface metrology, multi-scale geometric analyses, axiomatic design, sports engineering, and manufacturing process.

M. S. Fofana, Associate Professor, Ph.D., University of Waterloo, Waterloo, Canada, 1993; Nonlinear delay dynamical systems, stochastic bifurcations, regenerative chatter, numerically controlled CAD/CAM machining.

S. A. Johnson, Professor; Ph.D., Cornell University, 1989; Lean process design, enterprise engineering, process analysis and modeling, reverse logistics.

D. A. Lados, Milton Prince Higgins II Distinguished Associate Professor of Mechanical Engineering; Director, Integrative Materials Design Center (iMdc); Ph.D., Worcester Polytechnic Institute, 2004; Fatigue, fatigue crack growth, and fracture of metallic materials – life predictions, computational modeling and ICME, materials/process design and optimization for aerospace, automotive, marine, and military applications.

M. M. Makhlouf, Professor; Ph.D., Worcester Polytechnic Institute. Solidification of Metals, the application of heat, mass and momentum transfer to modeling and solving engineering materials problems, and processing of ceramic materials.

D. Strong, Professor of Management; Ph.D., Carnegie-Mellon University; Director of the Management Information Systems (MIS) Program; MIS and work flows, data integration and role changes; MIS quality issues, data and information quality.

B. Tulu, Associate Professor of Management, Ph.D. Claremont Graduate University. Medical informatics, information security, telemedicine, personal health records, systems analysis and design.

A. Zeng, Professor of Operations Management; Assistant Dean; Director of Operations & Industrial Engineering Program; Ph.D., Pennsylvania State University.

Faculty Research Interests

Current research areas include tolerance analysis, CAD/CAM, production systems analysis, machining, fixturing, delayed dynamical systems, nonlinear chatter, surface metrology, fractal analysis, surface functionality, metals processing and manufacturing management, axiomatic design, and abrasive processes, electronic medical records, lean in health care and health dynamics.

Programs of Study

The Manufacturing Engineering (MFE) Program offers two graduate degrees: the master of science and the doctor of philosophy. Full- and part-time study is available.

The graduate programs in manufacturing engineering provide opportunities for students to study current manufacturing techniques while allowing each student the flexibility to customize their educational program. Course material and research activities often draw from the traditional fields of computer science, controls engineering, electrical and computer engineering, environmental engineering, industrial engineering, materials science and engineering, mechanical engineering, and management. The program's intention is to build a solid and broad foundation in manufacturing theories and practices, and allow for further concentrated study in a selected specialty.

Admission Requirements

Candidates for admission must meet WPI's requirements and should have a bachelor's degree in science, engineering, or management, preferably in such fields as computer science/engineering, electrical/ control engineering, industrial engineering, environmental engineering, manufacturing engineering, materials science and engineering, mechanical engineering, or management. Students with other backgrounds will be considered based on their interest, formal education and experience in manufacturing.

Degree Requirements

For the M.S.

The Manufacturing Engineering (MFE) program is intended to be flexible in order to meet student needs. Many MFE graduate students work full time as engineers, others are graduate teaching and research assistants. Many of the courses are offered in the evenings.

The M.S. Degree in MFE requires 30 credit hours of graduate studies. The 30 credits consist of a minimum of 12 credit hours of coursework, plus 18 credit hours of any combination of coursework, independent study, directed research or thesis that complies with the following constraints: if there is a thesis, it must be at least 6 and no more than 12 credits; there can be no more than 9 credits of directed research; and the total number of credits from the Management Department cannot exceed 14.

The minimum of 12 credit hours of coursework must include a minimum of two credits each in at least four of the eight core areas. The coursework should be selected in consultation with an advisor from the MFE faculty. All full-time students are required to participate in the non-credit seminar course MFE 500.

The eight core areas, and corresponding suggested courses that students can select from to fulfill the requirements in each of these areas, are listed below. Courses that appear in more than one core area can only be used to fulfill the requirements in one.

1. Manufacturing Systems

1.1. MFE 531 Computer Integrated Manufacturing

1.2. OIE 544 Supply Chain Analysis and Design

1.3. OIE 548 Productivity Management

1.4. OIE 555 Lean Process Design

1.5. MIS 573 System Design and Development

1.6. MIS 584 Business Intelligence

2. Manufacturing Processes

2.1. MFE 520 Design and analysis of Manufacturing Processes

2.2. MFE 511 Industrial Robotics

Or any graduate Manufacturing Engineering or Materials Science and Engineering course on a manufacturing process

3. Control Systems

3.1. MFE 510 Control and Monitoring of Manufacturing Processes

3.2. MFE 511 Industrial Robotics

Or any graduate course in the Dynamics and Controls section of Mechanical Engineering

4. Design

4.1. MFE 541 Design for Manufacturability

4.2. MFE 520 Design and Analysis of Manufacturing Processes

4.3. ME 545 Computer-aided Design and Geometric Modeling

5. Materials

Any graduate course in Materials Science and Engineering

6. Financial Processes

6.1. ACC 501 Financial Accounting

6.2. FIN 502 Finance

6.3. FIN 508 Economics of the Firm

6.4. FIN 509 Domestic and Global Economic Environment of Business

6.5. ACC 514 Business Analysis for Technological Managers (prerequisites: ACC 501, FIN 502, OIE 505, MKT 506 and FIN 508)

7. Statistics and Quality Assurance

7.1. OIE 505 Quantitative Methods

7.2. MKT 506 Principles of Marketing

7.3. OIE 558 Designing and Managing Six-Sigma Processes

Or any graduate Mathematical Sciences course on statistics

8. Health Systems Engineering

MIS 571. Database Applications Development

MIS 579 E-Business Applications

OIE 541 Operations Risk Management

SD 550 Foundation: Managing Complexity

SD 551 Modeling and Experimental Analysis of Complex Problems

CS 505 Social Implications of Computing

BME 560 Physiology for Engineers

Suggested courses from other cores:

MIS 573 System Design and Development can be taken as part of Manufacturing Systems

MIS 584 Business Intelligence can be taken as part of Manufacturing Systems

OIE 555 Lean Process Design can be taken as part of Manufacturing Systems

MFE 520 Design and Analysis of Manufacturing Processes can be taken as part of Design

OIE Quantitative Methods can be taken as part of Statistics and Quality

OIE Designing and Managing Six-Sigma Processes can be taken as part of Statistics and Quality

A course taken from the Financial Processes core

For the Ph.D.

The doctoral (Ph.D.) program in MFE is a research degree with no required courses. All candidates must pass a comprehensive exam. All candidates must complete at least one year in residence, have a dissertation proposal accepted, then complete the dissertation and defend it successfully.

The dissertation is based on original research. A broad range of research topics is possible, including investigation into the fundamental science on which manufacturing processes are based, material science, manufacturing engineering education, metrology, quality, machine tool dynamics, manufacturing processes, design methodology and production systems, and health systems research.

MFE Seminar

Seminar speakers include WPI faculty and students as well as manufacturing experts and scholars from around the world. Registration for, attendance at and participation in the seminar course, MFE 500, is required for full-time students. The seminar series provides a common forum for all students to discuss current issues in manufacturing engineering.

Research Facilities and Laboratories

The CAM Laboratory

The CAM Lab facilitates the use of digital technologies to model, analyze, and control the manufacturing processes and systems. Besides the computers available for students, several application software packages have been used for CAD, solid modeling, kinematic analysis, FEA, modeling and simulation of machining and other materials processing, as well as new additive manufacturing processes. The lab has been developing techniques and systems for process (machining and heat treatment) modeling and simulation, production planning, tolerance analysis, fixture design, and lean manufacturing.

Manufacturing Interpreting Robotics Analysis Delay Dynamical Systems Laboratory (MIRAD)

The MIRAD laboratory focuses on developing computation, technology and engineering to better improve emergency medical services, ambulance vehicles, dialysis treatment, medical and public health systems, aircraft breaking systems, systems engineering mechanics and automated manufacturing systems design. Our innovative computerized modelling techniques, simulations, experiments and computer-controlled data acquisition to understand vibrations and quantify uncertainty enable us to estimate optimal performance reliance of products, processes and systems in sustained ways. The partners of MIRAD Laboratory include but not limited to industry, academia, hospitals, EMS departments, research institutions and universities.

Manufacturing Laboratories

The manufacturing laboratories are spread out in six main areas in two buildings and house WPI's Haas Technical Education Center as well as WPI's Robotics Resource Laboratory, WPI's Collablab, and several student work spaces. In the Higgins Laboratories the facilities are located in rooms 004, 005, and 006. In the Washburn Shops the facilities are located in rooms 105, 107, and 108. The facilities are operated by an operations manager, and two lab machinists who are assisted by up to 20 undergraduate peer learning assistants (PLAs). Over 1000 WPI students use the facilities each year completing hundreds of individual and group projects. In a typical 7 week term we record over 4000 instances of use in the facilities which are available for student use 24 hours per day 365 days per year.

The Haas Technical Education Center was established with a $400,000 award from the Fleet Asset Management, trustee of the Elizabeth A. Lufkin Trust and Haas Automation, Oxnard, California, and represented in New England by Trident Machine tools, who entrusted WPI with over a quarter million dollars in new machine tools, software and training.

The center is used for both undergraduate teaching and graduate research. The eleven CNC machine tools are used in ME 1800, ME 3820, and ES 3323, as well as other courses. The machine tools facilitate the realization, i.e. fabrication, of parts that students have designed on computers. The machine tools are important for supporting WPI's project based-education. The machine tools are also be used in manufacturing engineering research, as well as to produce apparatus to support research efforts in other fields.

Higgins Machine Shop and Project Laboratory

The machine shop in the Higgins Labs consists of three adjacent areas: the Machine Shop (HL004, 600 sq. ft.), the Project Laboratory (HL005, 1600 sq. ft.), and the SAE Project Lab (HL006, 300 sq. ft.). The Machine Shop contains 2 CNC Machine tools (a Haas Tool Room min and a Haas Tool Room Lathe), as well as a surface grinder, 2 DoAll Mills and a DoAll engine lathe as well as a drill press, 2 band saws and assorted hand tools A machinist manages and supports the machine shop and project activities with the assistance of undergraduate PLAs. The Project Laboratory is used primarily for the conduct of capstone design projects requiring a large work and assembly area, such as the SAE Formula Race Car and other SAE projects. Typically, 12 –15 students are involved with the projects in this laboratory throughout the academic year.

In addition to providing space for capstone design projects the project lab also provides space to one of WPI's US First Robotics teams and supports the Robotics Resource Center, as well as being the home of WPI's CollabLab. The CollabLab is a student organization that promotes "maker" culture and collaboration at WPI.

Robotics Laboratory

The Robotics Laboratory, a 1,915 sq. ft. facility, is located on the first floor of the Washburn Building room 108 is equipped with a variety of industrial robots, machine tools and other equipment. The industrial robots, for which the Robotics Laboratory is named, are run primarily during the laboratory sessions of the Industrial Robotics course (ME 4815), and to a lesser extent by undergraduate project groups and graduate researchers. The industrial robots in the laboratory include: one Fanuc LR Mate 200iB, and one Fanuc M-710iC. . The Robotics lab houses four of the five entrusted machine tools that are part of WPI's Haas Technical Education Center. The Mill Drill Center (MDC) is a permanent entrustment and has duel pallets so a part can be loaded while the machine is cutting. This machine is frequently used in conjunction with the Fanuc LR Mate. The Haas ST30-Y fully automated 4 axis machining center with an automatic bar feeder. Used in conjunction with the Fanuc ----- and the MDC students can create a fully automated production cell. Both the Haas VM2 and VF4-SS also located in the Robotics Lab are equipped with full 5 axis control systems. We have a Haas fifth axis fixturing system that can be mounted in either machine tool.

CNC Teaching Laboratory

The CNC teaching laboratory is located in the Washburn Shops Room 107 and covers 3,140 sq. ft. The mission of the CNC labs is to support the mission of WPI, by creating, discovering, and conveying knowledge at the frontiers of inquiry in CNC machining and education, as well as linking that new knowledge to applications; help students achieve self-sufficiency in the use of CNC tools and technologies, so they can conceive, design, and create their own CNC machined parts for their projects.

The vision of the CNC labs is to be the premier laboratory for CNC engineering education and research (applied and fundamental) in the world.

In the teaching laboratory we have one Universal Laser Systems VLS60 Laser Cutter, one Makerbot Replicator 2X, 3 Haas MiniMills and 2 Haas SL10s, 3 band saws, two drill presses, a sheet metal shear and bending break as well as assorted hand tools. Attached to each of the MiniMills and SL10s are computer workstations equipped with all of the design and programming software supported on campus and with our instructional tools that have been developed to allow students to train each other.

In addition to the computers located at each of the CNC machine tools in the CNC teaching laboratory and robotics laboratories the facility has two computer classroom spaces one located in 107 with the other in 105. Each of the classroom spaces can be configured to contain between 8 and 12 computer workstations. Each space also has, a conference table, whiteboards, and a ceiling mounted projector that each computer in the space can send its signal to when the spaces are used for project group meetings.

Students working on any of the computer workstations in the facilities have access to the design software packages supported on campus as well as our training materials and several Computer Aided Manufacturing (CAM) software packages including Esprit, MasterCam, and SurfCam.

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Metal Processing Institute (MPI)

The Metal Processing Institute (MPI) is an industry-university alliance. Its mission is to design and carry out research projects identified in collaboration with MPI's industrial partners in the field of near and net shape manufacturing. MPI develops knowledge that will help enhance the productivity and competitiveness of the metal processing industry and develops the industry's human resource base through the education of WPI students. Over 90 corporate partners participate in the Institute, and their support helps fund fundamental and applied research that addresses technological barriers facing the industry. MPI is one of WPI's two Institutes with a legacy based on Theory and Practice. MPI houses three centers: the Advanced Casting Research Center (ACRC); the Center for Heat Treating Excellence (CHTE); and the Center for Resource Recovery and Recycling (CR3). The latter is a multi-university center with CSM and KU Leuven.

Surface Metrology Laboratory

WPI's Surface Metrology Lab is one of just a few academic labs in the world that focuses on measurement and analysis of surface topographies, or roughness. Through the generosity of the respective companies the lab has the use of an Olympus LEXT OLS4100 laser scanning confocal microscope, a Solarius SolarScan white light microscope and a Mahr-Federal MarSurf GD25 stylus profiler for measuring topographies, as well as Mountains Map (DigitalSurf), Modal Filter, and Sfrax, software for analysis. We study how topographies are influenced by processing and influence the performance of surfaces. One task it to find ways to discriminate surfaces that were processed differently, or that perform differently, based on topographic measurement and analysis. Another task is to find functional correlations between topographies and their processing or their performance. The lab has pioneered the development and application of several kinds of multi-scale analyses including geometric and fractal analyses for discrimination and correlation. The lab serves industry and collaborates with engineers and scientists from a variety of disciplines around the world.

Course Descriptions

All courses are 3 credits unless otherwise noted.

MFE 500. Current Topics in Manufacturing Seminar

(0 credits)

This seminar identifies the typical problems involved in a variety of manufacturing operations, and generic approaches for applying advanced technologies to implement operations. Topical areas of application and development such as intelligent materials processing, automated assembly, MRP and JIT scheduling, vision recognition systems, high-speed computer networks, distributed computer control of manufacturing processes and flexible manufacturing systems may be covered. This seminar is coordinated with the undergraduate program in manufacturing engineering. *Required for all full-time students.*

MFE 510. Control and Monitoring of Manufacturing Processes

(3 Credits)

Covers a broad range of topics centered on control and monitoring functions for manufacturing, including process control, feedback systems, data collection and analysis, scheduling, machine-computer interfacing and distributed control. Typical applications are considered with lab work.

MFE 511. Application of Industrial Robotics

(2 Credits)

(Concurrent with ME 4815) This course introduces the student to the field of industrial automation. Topics covered include robot specification and selection, control and drive methods, part presentation, economic justification, safety, implementation, product design and programming languages. The course combines the use of lecture, project work and laboratories that utilize industrial robots. Theory and application of robotic systems will be emphasized.

MFE 520/MTE 520/ME 543. Axiomatic Design of Manufacturing Processes

(3 Credits)

This course begins with elements axiomatic design, the theory and practice. Design applications are considered primarily, although not exclusively, for the design of manufacturing processes and tools. Axiomatic design is based on the premise that there are common aspects to all good designs. These commons aspects, stated in the independence and information axioms, facilitate the teaching and practice of engineering design as a scientific discipline. Analysis of processes and products is considered from the perspective of supporting product and process design. Fundamental methods of engineering analysis of manufacturing processes with broad applicability are developed. Attention is given to examples from one or more of the following: machining (traditional, nontraditional and grinding), additive manufacturing, and to the production of surface topographies. The ability to generalize from detailed examples is emphasized in order to facilitate the students' ability to development analyses and design methods with broader applicability.

This course is offered live, in-class only, to be completed in one semester, for three credits. Credit cannot be given for this course and any of the similar, on-line versions of this material for 2 credits: MFE 521, MTE 521 and ME 521.

MFE/MTE 521. Fundamentals of Axiomatic Design of Manufacturing Processes

(2 credits)

The course starts with an in-depth study of axiomatic design. Applications of axiomatic design are considered primarily, although not exclusively, for the design of manufacturing processes and tools. Axiomatic design is a design methodology based on the premise that there are two axioms that apply to all good designs. These axioms facilitate the teaching and practice of engineering design as a scientific discipline. Manufacturing process analysis is considered from the perspective of supporting design. Methods of analysis of manufacturing processes with broad applicability are sought. Special attention is given to examples in machining (traditional, nontraditional and grinding), additive manufacturing, and to the production of surfaces. The ability to find commonalities across applications and generalize is emphasized to facilitate further development of principles with broad applicability. The content is delivered in video lectures and in readings from the technical literature. Homework and quizzes are given and delivered on-line. There is a project to design a manufacturing process. The topics can be from work or dissertations that can be interpreted as manufacturing processes and tools.

Credit cannot be given for this course and any of the similar, in-class versions for 3 credits, MFE 520, MTE 520 and ME 543

MFE 531/ME 5431. Computer Integrated Manufacturing
(2 Credits)

An overview of computer-integrated manufacturing (CIM). As the CIM concept attempts to integrate all of the business and engineering functions of a firm, this course builds on the knowledge of computer-aided design, computer-aided manufacturing, concurrent engineering, management of information systems and operations management to demonstrate the strategic importance of integration. Emphasis is placed on CAD/CAM integration. Topics include, part design specification and manufacturing quality, tooling and fixture design, and manufacturing information systems. This course includes a group term project. (Prerequisites: Background in manufacturing and CAD/CAM, e.g., ME 1800, ES 1310, ME 3820.) Note: Students cannot receive credit for this course if they have taken the Special Topics version of the same course (MFE 593D/MFE 594D).

MFE 541/ME 5441. Design For Manufacturability
(2 Credits)

The problems of cost determination and evaluation of processing alternatives in the design-manufacturing interface are discussed. Approaches for introducing manufacturing capability knowledge into the product design process are covered. An emphasis is placed on part and process simplification, and analysis of alternative manufacturing methods based on such parameters as: anticipated volume, product life cycle, lead time, customer requirements, and quality yield. Lean manufacturing and Six-Sigma concepts and their influence on design quality are included as well. Note: Students cannot receive credit for this course if they have taken the Special Topics version of the same course (MFE594M).

MFE/MTE 5841. Surface Metrology
(3 Credits)

This course emphasizes research applications of advanced surface metrology, including the measurement and analysis of surface roughness. Surface metrology can be important in a wide variety of situations including adhesion, friction, catalysis, heat transfer, mass transfer, scattering, biological growth, wear and wetting. These situations impact practically all the engineering disciplines and sciences. The course begins by considering basic principles and conventional analyses, and methods. Measurement and analysis methods are critically reviewed for utility. Students learn advanced methods for differentiating surface textures that are suspected of being different because of their performance or manufacture. Students will also learn methods for making correlations between surface textures and behavioral and manufacturing parameters. The results of applying these methods can be used to support the design and manufacture of surface textures, and to address issues in quality assurance. Examples of research from a broad range of applications are presented, including, food science, pavements, friction, adhesion, machining and grinding. Students do a major project of their choosing, which can involve either an in-depth literature review, or surface measurement and analysis. The facilities of WPI's Surface Metrology Laboratory are available for making measurements for selected projects. Software for advanced analysis methods is also available for use in the course. No previous knowledge of surface metrology is required. Students should have some background in engineering, math or science.

MFE 594. Special Topics

Theoretical and experimental studies in subjects of interest to graduate students in manufacturing engineering. (Prerequisite: Consent of instructor.) The description of each Special Topics course is attached to the course number as seen on the course schedule posted on the Registrar's website.

MFE 598. Directed Research

MFE 599. Thesis Research

www.wpi.edu/+MPE

Materials Process Engineering

Faculty

R. D. Sisson, Jr., George F. Fuller Professor, Director of Manufacturing and Materials Engineering: Ph.D., Purdue University

Faculty from Management, Manufacturing Engineering, Materials Science and Engineering to Mechanical Engineering, and Systems Engineering work with this program. See those programs for complete faculty listings.

Program of Study

The founders of Worcester Polytechnic Institute made their fortunes in the materials processing industries of wire drawing (Ichabod Washburn) and tin smithing (John Boynton). Since classes began in 1868, WPI has prepared young men and women for careers in materials processing. Many WPI alumni and faculty members have established materials processing companies including Norton Company, Wyman-Gordon, and PresMet.

WPI's Materials Process Engineering (MPE) Master of Science graduate degree program continues this outstanding legacy by providing engineers, scientists and managers with the knowledge, skills and experience to become the entrepreneurs, trend setters and executives in the materials processing industry in the 21st century. This 30-credit program offers the opportunity for serious professionals to become leaders by selecting courses from three programs:

Manufacturing Engineering
Materials Science and Engineering
Management/Industrial Engineering

Admission Requirements

Admission requirements include a B.S. in engineering or science. The program is designed to be completed in three to four years while working full time. Classes are offered on campus one evening or two afternoons per week. Many classes are available through WPI's Corporate Online Graduate Programs.

Degree Requirements

For the M.S.

Course Requirements

For the master of science in materials process engineering, the student is required to complete a minimum of 30 graduate credit hours as follows:

Materials Science and Engineering Graduate Courses

(9 or more credits)

- MTE 511 Structure and Properties of Engineering Materials
- MTE 512 Properties and Performance of Engineering Materials
- MTE 526 Advanced Thermodynamics
- MTE 532 X-Ray Diffraction and Crystallography
- MTE 540 Analytical Methods in Materials Engineering
- MTE 550 Phase Transformations in Materials
- MTE 561 Mechanical Behavior and Fracture of Materials
- MTE 5844 Corrosion and Corrosion Control
- Any other MTE 5XX course

Manufacturing Engineering Graduate Courses

(6 credits)

- MFE 510 Control and Monitoring of Manufacturing Processes
- MFE 520 Design and Analysis of Manufacturing
- MFE 531 Computer Integrated Manufacturing
- MFE 541 Design for Manufacturability
- MFE 5841 Surface Metrology: Measurement and Analysis of Surface Textures
- Any other MFE 5XX course

Management/Industrial Engineering Graduate Courses

(9 credits)

These credits may be selected from any graduate management graduate courses. Typically, students will select from Operations and Industrial Engineering (OIE) or Entrepreneurship (ETR) topics. However courses from other topical areas in management may be selected.

Electives (3 credits)

To ensure flexibility in this program, each student will select 3 credits of electives from any graduate-level course at WPI. Electives are typically selected from the topics listed here; however, electives from mathematics, chemistry, physics, computer science, social science, or any engineering program may be acceptable. Courses in nanotechnology and MEMS are also available.

MPE Project (3 credits)

Each student must complete the MPE project. This may be a team or independent project sponsored by industry. The project must address several issues in business analysis, operations, process design and quality, as well as the processing/structure/property relationships in the process being studied. The culmination of this project will be a business plan and/or a research proposal or a new product. The final report is presented in a seminar or class in materials science, manufacturing engineering, or management.

After at least twenty graduate credits have been successfully completed, the student registers for the 3-credit project with one or more faculty advisors. The project is completed over a 14-week semester. Ideally, the project is completed by a team of three; however, smaller or larger teams will be considered. Working with a faculty advisor, the team develops a clear statement of the goals and objectives of the project. Weekly meetings with the advisor with written and oral reports are required. The culmination of the project is a business plan and/or a research proposal or a new product. The project should integrate the skills obtained and knowledge acquired in the student's coursework as well as industrial experience.

Materials Science and Engineering

www.wpi.edu/+MPE

Faculty

R. D. Sisson Jr., George F. Fuller Professor; Director, Manufacturing and Materials Engineering; Ph.D., Purdue University. Materials process modeling and control, manufacturing engineering, corrosion, and environmental effects on metals and ceramics.

D. Apelian, Alcoa/Howmet Professor of Engineering; Director, Metal Processing Institute; Sc.D., Massachusetts Institute of Technology. Resource recovery and recycling, solidification processing, spray casting, molten metal processing, aluminum foundry processing, plasma processing, and knowledge engineering in materials processing.

I. Bar-On, Professor; Ph.D., Hebrew University of Jerusalem. Mechanical behavior of materials, fracture and fatigue of metals, ceramics and composites, reliability and lie prediction, and electronic packaging.

R. R. Biederman, Professor Emeritus; Ph.D., P.E., University of Connecticut. Materials science and engineering, microstructural analysis, SEM, TEM, and diffraction analysis.

C. A. Brown, Professor; Director, Surface Metrology Lab; Ph.D., University of Vermont. Surface metrology, multi-scale geometric analyses, axiomatic design, sports engineering, and manufacturing processes.

D. Cote, Assistant Research Professor, Director of Center for Materials Processing Data (CMPD); Ph.D., Worcester Polytechnic Institute. Computational thermodynamics and kinetics; Phase transformations; Powder metallurgy.

C. Demetry, Associate Professor; Director of the Morgan Teaching and Learning Center, Ph.D., Massachusetts Institute of Technology. Materials science and engineering education, nanocrystalline materials and nanocomposites, ceramics, and grain boundaries and interfaces in materials.

M. H. Emmert, Associate Professor of Chemistry; Ph.D., Universität Münster, Germany. Transition metal catalysts for C-H functionalization and CO2 reduction, sustainable syntheses, and new reagents for direct aminations of C-H bonds.

D. A. Lados, Milton Prince Higgins II Distinguished Associate Professor of Mechanical Engineering; Director, Integrative Materials Design Center (iMdc); Ph.D., Worcester Polytechnic Institute, 2004. Fatigue, fatigue crack growth, thermo-mechanical fatigue, creep, and fracture of metallic materials – life predictions, computational modeling and ICME, materials/process design and optimization for aerospace, automotive, marine, and military applications; advanced material characterization; additive manufacturing, metal matrix nano–composites, friction stir welding, cold spray technology, powder metallurgy; residual stress; plasticity; fracture mechanics.

Jianyu Liang, Associate Professor, Ph.D., Brown University, 2004. Nanostructured materials, material processing, material characterization.

M. M. Makhlouf, Professor; Ph.D., Worcester Polytechnic Institute. Solidification of Metals, the application of heat, mass and momentum transfer to modeling and solving engineering materials problems, and processing of ceramic materials.

B. Mishra, Kenneth G. Merriman Professor, Director of Metal Processing Institute: Ph.D., University of Minnesota, MN. Physico-chemical processing of materials; Corrosion science and engineering; Materials Processing, Surface Engineering, Resource Recovery & Recycling, Critical materials extraction; Iron and steelmaking; Alloy development; Thin film coatings.

P. Rao, Assistant Professor of Mechanical Engineering; Ph.D., Stanford University. Flame synthesis of nanomaterials for solar energy conversion and storage.

S. Shivkumar, Professor; Ph.D., Stevens Institute of Technology. Biomedical materials, plastics, materials processing.

W. Soboyejo, Bernard M. Gordon Dean of Engineering, Professor of Engineering Leadership; Ph.D., Cambridge University. Materials Science, Biomaterials, Materials for Energy Systems and Multifunctional Materials for Sustainable Development.

L. Wang, Research Professor of Mechanical Engineering; Ph.D., Drexel University. Casting technology, aluminum casting alloy development and characterization, heat treatment, molten metal processing, and solidification processing.

Y. Wang, William Smith Foundation Dean's Professor, Associate Professor of Mechanical Engineering; Ph.D., University of Windsor (Canada). Lithium ion battery, fuel cell, corrosion and electrochemistry, flow battery.

Program of Study

Materials Science and Engineering (MTE) offers programs leading to a degree of master of science and/or doctor of philosophy.

The master of science in materials science and engineering provides students with an opportunity to study the fundamentals of materials science and state-of-the-art applications in materials engineering and materials processing. The program is designed to build a strong foundation in materials science along with industrial applications in engineering, technology and processing. Both full- and part-time study are available.

Program areas for the doctor of philosophy emphasize the processing-structure-property-performance relationships in metals, ceramics, polymers and composites. Current projects are addressing these issues in fuel cell materials, biopolymers, aluminum and magnesium casting, the heat-treating of steels and aluminum alloys and metal matrix composites.

Well-equipped laboratories within Washburn Shops and Stoddard Laboratories include such facilities as scanning (SEM) and transmission (TEM) electron microscopes, X-ray diffractometer, process simulation equipment, a mechanical testing laboratory including two computer-controlled servohydraulic mechanical testing systems, metalcasting, particulate processing, semisolid processing laboratories, a surface metrology laboratory, a metallographic laboratory, a polymer engineering laboratory with differential scanning calorimeter (DSC)

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and thermo gravimetric analyzer (TGA), a corrosion laboratory, topographic analysis laboratory and machining force dynamometry. A range of materials processing, fastening, joining, welding, machining, casting and heat treating facilities is also available.

Admission Requirements

The program is designed for college graduates with engineering, mathematics or science degrees. Some undergraduate courses may be required to improve the student's background in materials science and engineering. For further information, see page 11.

Degree Requirements

For the M.S.

For the master of science in materials science and engineering, the student is required to complete a minimum of 30 graduate credit hours. Requirements include MTE 511 and MTE 512 and at least 4 of the following courses: MTE 526, MTE 532, MTE 540, MTE 550, MTE 561. For the remaining credits, the student may choose between a thesis or coursework option and Directed Research.

Thesis Option

The student must complete a thesis with a minimum of 6 graduate credits. Additional thesis credits may substitute for course electives. The remaining graduate credits must consist of additional MTE or other 4000-, 500- or 600-level engineering, science, management or mathematics electives. All courses must be approved by the student's advisor and the Materials Graduate Committee.

Non Thesis Option

The student must complete a three credit capstone project or equivalent that demonstrates the ability to design, implement, and complete an independent professional project. The remaining graduate credits must consist of additional MTE or other 4000-, 500- or 600-level engineering, science, management or mathematics electives. All courses must be approved by the student's advisor and the Materials Graduate Committee.

Satisfactory participation in the materials engineering seminar (MTE 580) is also required for all full-time students. In addition to general college requirements, all courses taken for graduate credit must result in a GPA of 3.0 or higher. Waiver of any of these requirements must be approved by the Materials Science and Engineering Graduate Committee, which will exercise its discretion in handling any extenuating circumstances or problems.

Examples of Typical Program

- Materials engineering core courses—18 credits
- Electives—6 credits
- Thesis—6 credits
- **Total—30 credits**

For the Ph.D.

The number of course credits required for the doctor of philosophy degree, above those for the master of science, is not specified precisely. For planning purposes, the student should consider a total of 21 to 30 course credits. The remainder of the work will be in research and independent study. The total combination of research and coursework required will not be less than 60 credits beyond the master of science degree or not less than 90 credits beyond the bachelor's degree.

Admission to candidacy will be granted only after the student has satisfactorily passed the Materials Engineering Doctoral Qualifying/ Comprehensive Examination (MEDQE). The purpose of this exam is to determine if the student's breadth and depth of understanding of the fundamental areas of materials engineering is adequate to conduct independent research and successfully complete a Ph.D. dissertation.

The MEDQE consists of both written and oral components. The written exam must be successfully completed before the oral exam can be taken. The oral exam is usually given within two months of the completion of the written exam. The MEDQE is offered at least one time each year.

A member of the materials science and engineering faculty will be appointed to be the chairperson of the MEDQE Committee. This person should not be the student's Ph.D. thesis advisor; but that advisor may be a member of the MEDQE Committee. Others on the committee should be the writers of the four sections of the examinations and any other faculty selected by the chairperson. Faculty from other departments at WPI or other colleges/universities, as well as experts from industry, may be asked to participate in this examination if the materials engineering faculty deems that it is appropriate.

At least one year prior to completion of the Ph.D. dissertation, the student must present a formal seminar to the public describing the proposed dissertation research project. This Ph.D. research proposal will be presented after admission to candidacy.

Materials Science and Engineering Laboratories and Research Centers

Electrochemical Energy Laboratory

The electrochemical energy laboratory is equipped for analyzing a variety of electrochemical reactions. Examples of these reactions include electrolysis of metal salts for primary metal production, lithium ion transport in lithium ion batteries and reactions involved in colloidal flow battery suspensions. The equipment includes three different electrochemical analyzers (Bio-logic electrochemical tester with 10 channels, Newware Battery testing system, Arbin BT2043 with MitsPro4.0 System), and a two-person MBRAUN Glovebox. Additionally several furnaces, oven, high energy ball mill, overhead stirrer, spin coater and a hydraulic press are available for electrode preparation. The lab also includes a Shutte Buffalo W-6-H hammer-mill for recycling related projects.

Integrative Materials Design Center (iMdc)

iMdc is a WPI-based research center dedicated to advancing the state-of-the-art-and-practice in sustainable materials-process-component design and manufacturing for high-performance, reliability, and recyclability through knowledge creation and dissemination, and through education.

iMdc is formed through an industry-government-university alliance, and its program is built in direct collaboration, and with active participation and insight from its industrial and government partners.

The center is conducting fundamental research, which addresses well-identified industrial applications of general interest and relevance to the manufacturing sector.

The overarching objective of the iMdc's research portfolio is to prevent failure and increase high–performance and reliability of high-integrity structures through:

- Exploring and advancing the fundamental and practical understanding of a wide range of multi-scale metallic and composite materials and their respective processes
- Developing new and optimized materials and processing practices, including recycling as a design factor
- Establishing knowledge-based microstructure-properties-performance relationships
- Investigating the impact of increased utilization of recycled materials in high-performance materials and applications
- Providing practical and integrated design and computational (ICME) methods and tools
- Identifying and pursuing implementation venues for the developed materials, processes, and design methodologies

Industrial and government partners review and provide insight and guidance to the research programs, bring industrial perspective, and assist in identifying strategies for the implementation of the developments in the industry. This setting provides a platform for creating knowledge in a well-defined context while being able to disseminate it and witness its implementation and impact in/on actual industrial applications.

Materials Characterization Laboratory

The Materials Characterization Laboratory (MCL) is an analytical user facility, which serves the materials community at WPI, offering a range of analytical techniques and support services. Licensed users have 24/7 access to instruments including JEOL 7000F field-emission gun scanning electron microscope, JEOL 100CXII transmission electron microscope, PANalytical Empyrean x-ray diffractometer, Spectro MAXx LMX04 Spectrometer, Agilent Nanoindenter, Clark CM-400AT microhardness indenter, Shimazu HMV-2000 Microhardness tester, Buehler Microhardness tester, Rockwell hardness testers, and more than 10 grinding and polishing machines. The MCL is also open to researchers from other universities and local industries.

Metal Processing Institute (MPI)

The Metal Processing Institute (MPI) is an industry-university alliance dedicated to advancing available technology to the metal processing and materials recovery and recycling industries. Students, professors and more than 90 industry partners work together on research projects that address technological barriers facing industry – making member businesses more competitive and productive.

MPI offers educational opportunities and corporate resources to undergraduate and graduate students. They include:

- International exchanges and internships with several leading universities in Europe and Asia.
- Graduate internship programs leading to a master's or doctoral degree, where the research is carried out at the industrial site.

MPI's research programs are managed by three distinct research centers:

- Advanced Casting Research Center (ACRC) – more information below.
- Center for Heat Treating Excellence (CHTE) – more information below.
- Center for Resource Recovery and Recycling (CR3) – more information below.

For further information please visit the MPI offices on the third floor of Washburn, Room 326. Our visit our website: http://wpi.edu/+mpi

The Advanced Casting Research Center (ACRC)

The Advanced Casting Research Center (ACRC) brings industry and university together to collaborate on research projects in the areas of light metals, non-ferrous alloys and semi-solid processing. The advancements being made in the ACRC provide solutions to today's manufacturing challenges.

Undergraduate and graduate students working in the ACRC laboratories work directly with professional engineers from 34 sponsoring companies, as well as WPI faculty. The lab is equipped with leading-edge technology:

- Computerized data acquisition systems for solidification studies
- Thermal analysis units
- Liquid metal filtration apparatus
- Rheocasting machines
- Extensive melting and casting facilities
- Variety of heat treating furnaces

Student scholarships offered by the Foundry Education Foundation (FEF) and NADCA are available through ACRC, as are project opportunities at international sites.

The ACRC lab is open throughout the year for project activity and thesis work, as well as co-op and summer employment. http://wpi.edu/+acrc

Center for Heat Treating Excellence (CHTE)

At the Center for Heat Treating Excellence (CHTE) students get to work with industry leaders and WPI faculty to solve business challenges and improve manufacturing processes through applied research.

Students will have the opportunity to work with over 20 corporate members from various parts of the heat treating industry – commercial heat treaters, captive heat treaters, suppliers and manufacturers.

Research projects focus on:

- Reducing energy consumption
- Controlling microstructure and properties of metallic components
- Reducing processing time
- Minimizing production costs
- Achieving zero distortion
- Increasing furnace efficiency

Project opportunities, industrial internships, co-op opportunities and summer employment are available through CHTE. http://wpi.edu/+chte

Center for Resource Recovery and Recycling (CR^3)

In nature, nothing is wasted. The Center for Resource Recovery & Recycling (CR^3) is the premiere industry-university collaborative that works towards taking the waste from one process and utilizing it in another, establishing a closed loop system – just as nature would. CR^3's mission is to be the ultimate resource in material sustainability.

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Students who work with CR³ will work with industry leaders on technological advancements that recover and recycle materials from initial product design, through manufacture to end-of-life disposition. The end result: enhanced environmental conservation, and im proved energy and cost savings.

Recent projects include:

- Near 100% auto recycling rates
- Dist recovery and recycling improvements
- Recovery of valuable materials from waste fluorescent
- Transformation of waste streams to value added materials

CR³ is an Industry and University Center (I/UCRC) and is supported by the National Science Foundation (NSF). Partner universities include Colorado School of Mines and KU Leuven, Belgium. For more information: https://wpi.edu/+cr3

Center for Materials Processing Data (CMPD)

The Center for Materials Processing Data (CMPD) is a research consortium dedicated to generating and disseminating materials property data used in materials processing and manufacturing technologies. This data is unique in that it's often transient, and is therefore difficult to find, and generate. CMPD will both generate experimentally, as well as mine existing literature data. Then, data will be disseminated to Center members to be used in their own predictive models.

NanoEnergy Laboratory

Research in the NanoEnergy Lab targets the synthesis and study of ordered nanomaterials for energy conversion applications, particularly for converting solar energy to electrical or chemical energy. The goal is to use nanostructuring and scalable, economical synthesis methods to dramatically improve the energy conversion efficiency of earth-abundant, low-cost materials.

Projects in the NanoEnergy Lab focus on:

- Flame-synthesis of complex, hierarchical, ordered nanomaterials
- Design, synthesis and characterization of nanostructured materials for solar energy conversion (photovoltaic and photoelectrochemical)

Nanomaterials synthesis equipment in the NanoEnergy lab includes vapor deposition (flat-flame burner and multi-zone tube furnace), hydrothermal synthesis reactors, solution deposition (fume hood, spin-coater), and various furnaces for annealing materials. Light sources, integrating spheres, spectrometers, a potentiostat, electrochemical cells and chemical sensors are available for the characterization of optical, electronic and electrochemical properties of materials.

The NanoEnergy Lab is located in HL026. For further information, please see nanoenergy.wpi.edu.

Nanomaterials and Nanomanufacturing Laboratory

This laboratory is well-equipped for advanced research in controlled nano-fabrications and nanomanufacturing of carbon nanotubes, magnetized nanotubes, semiconducting, superconducting, magnetic, metallic arrays of nanowires and quantum dots. Nanomaterials fabrication and engineering will be carried out in this laboratory by different means, such as PVD (physical vapor deposition), CVD (chemical vapor deposition), PECVD (plasma enhanced CVD), RIE (reactive ion etching), ICP etching (induced coupled plasma), etc. Material property characterizations will be conducted, including optic, electronic, and magnetic property measurements. Nanostructured device design, implementation, and test will also be carried out in this lab.

Polymer Laboratory

This laboratory is used for the synthesis, processing and testing of plastics. The equipment includes: thermal analysis machines Perkin Elmer DSC 4, DSC 7, DTA 1400 and TGA 7; single-screw table-top extruder; injection molding facilities; polymer synthesis apparatus; oil bath furnaces; heat treating ovens; and foam processing and testing devices.

Surface Metrology Laboratory

WPI's Surface Metrology Lab is one of just a few academic labs in the world that focuses on measurement and analysis of surface topographies, or roughness. Through the generosity of the respective companies the lab has the use of an Olympus LEXT OLS4100 laser scanning confocal microscope, a Solarius SolarScan white light microscope and a Mahr-Federal MarSurf GD25 stylus profiler for measuring topographies, as well as Mountains Map (DigitalSurf), Modal Filter, and Sfrax, software for analysis. We study how topographies are influenced by processing and influence the performance of surfaces. One task it to find ways to discriminate surfaces that were processed differently, or that perform differently, based on topographic measurement and analysis. Another task is to find functional correlations between topographies and their processing or their performance. The lab has pioneered the development and application of several kinds of multi-scale analyses including geometric and fractal analyses for discrimination and correlation. The lab serves industry and collaborates with engineers and scientists from a variety of disciplines around the world.

Course Descriptions

All courses are 3 credits unless otherwise noted.

MTE 509. Electron Microscopy
(2 credits)

This course introduces students to the theory, fundamental operating principles, and specimen preparation techniques of scanning electron microscopy (SEM), transmission electron microscopy (TEM), and energy dispersive x-ray spectroscopy (EDS). The primary emphasis is placed on practical SEM, TEM, and x-ray microanalysis of materials. Topics to be covered include basic principles of the electron microscopy; SEM instrumentation, image formation and interpretation, qualitative and quantitative x-ray microanalysis in SEM; electron diffraction and diffraction contrast imaging in TEM. Various application examples of SEM and TEM in materials research will be discussed. Lab work will be included. The course is available to graduate students. Recommended background: CH 1020, PH 1120, and ES 2001 or equivalent. Note: Students cannot receive credit for this course if they have taken the Special Topics version of the same course.

MTE 511/ME 5311. Structure and Properties of Engineering Materials
(2 credits)

This course, (along with its companion course MTE 512 Properties and Performance of Engineering Materials), is designed to provide a comprehensive review of the fundamental principles of Materials Science and Engineering for incoming graduate students. In the first part of this 2 course sequence, the structure in materials ranging from the sub-atomic to the macroscopic including nano, micro and macromolecular structures will be discussed to highlight bonding mechanisms, crystallinity and defect patterns. Representative thermodynamic and kinetic

aspects such as diffusion, phase diagrams, nucleation and growth and TTT diagrams will be discussed. Major structural parameters that effect of performance in materials including plastics, metallic alloys, ceramics and glasses will be emphasized. The principal processing techniques to shape materials and the effects of processing on structure will be highlighted. (Prerequisites: senior or graduate standing or consent of the instructor.) Note: Students cannot receive credit for this course if they have taken the Special Topics version of the same course (MTE 594S).

MTE 512/ME 5312. Properties and Performance of Engineering Materials
(2 credits)

The two introductory classes on materials science (MTE 511 and MTE 512) describe the structure-property relationships in materials. The purpose of this class is to provide a basic knowledge of the principles pertaining to the physical, mechanical and chemical properties of materials. The primary focus of this class will be on mechanical properties. The thermal, tensile, compressive, flexural and shear properties of metallic alloys, ceramics and glasses and plastics will be discussed. Fundamental aspects of fracture mechanics and viscoelasticity will be presented. An overview of dynamic properties such as fatigue, impact and creep will be provided. The relationship between the structural parameters and the preceding mechanical properties will be described. Basic composite theories will be presented to describe fiber-reinforced composites and nanocomposites. Various factors associated with material degradation during use will be discussed. Some introductory definitions of electrical and optical properties will be outlined. (Prerequisites: MTE 511 and senior or graduate standing or consent of the instructor) Note: Students cannot receive credit for this course if they have taken the Special Topics version of the same course (MTE 594P).

MTE 520/MFE 520/ME 543. Axiomatic Design of Manufacturing Processes
(3 credits)

This course begins with elements axiomatic design, the theory and practice. Design applications are considered primarily, although not exclusively, for the design of manufacturing processes and tools. Axiomatic design is based on the premise that there are common aspects to all good designs. These commons aspects, stated in the independence and information axioms, facilitate the teaching and practice of engineering design as a scientific discipline. Analysis of processes and products is considered from the perspective of supporting product and process design. Fundamental methods of engineering analysis of manufacturing processes with broad applicability are developed. Attention is given to examples from one or more of the following: machining (traditional, nontraditional and grinding), additive manufacturing, and to the production of surface topographies. The ability to generalize from detailed examples is emphasized in order to facilitate the students' ability to development analyses and design methods with broader applicability.

This course is offered live, in-class only, to be completed in one semester, for three credits. Credit cannot be given for this course and any of the similar, on-line versions of this material for 2 credits: MFE 521, MTE 521 and ME 521.

MTE/MFE 521. Fundamentals of Axiomatic Design of Manufacturing Processes
(2 credits)

The course starts with an in-depth study of axiomatic design. Applications of axiomatic design are considered primarily, although not exclusively, for the design of manufacturing processes and tools. Axiomatic design is a design methodology based on the premise that there are two axioms that apply to all good designs. These axioms facilitate the teaching and practice of engineering design as a scientific discipline. Manufacturing process analysis is considered from the perspective of supporting design. Methods of analysis of manufacturing processes with broad applicability are sought. Special attention is given to examples in machining (traditional, nontraditional and grinding), additive manufacturing, and to the production of surfaces. The ability to find commonalities across applications and generalize is emphasized to facilitate further development of principles with broad applicability. The content is delivered in video lectures and in readings from the technical literature. Homework and quizzes are given and delivered on-line. There is a project to design a manufacturing process. The topics can be from work or dissertations that can be interpreted as manufacturing processes and tools.

Credit cannot be given for this course and any of the similar, in-class versions for 3 credits, MFE 520, MTE 520 and ME 543.

MTE 526. Advanced Thermodynamics
(2 credits)

Thermodynamics of solutions—phase equilibria— Ellingham diagrams, binary and ternary phase diagrams, reactions between gasses and condensed phases, reactions within condensed phases, thermodynamics of surfaces, defects and electrochemistry. Applications to materials processing and degradation will be presented and discussed. (Prerequisites: ES 3001, ES 2001) Note: Students cannot receive credit for this course if they have taken the Special Topics version of the same course (MTE 594T).

MTE 532. X-Ray Diffraction and Crystallography
(2 credits)

This course discusses the fundamentals of crystallography and X-ray diffraction (XRD) of metals, ceramics and polymers. It introduces graduate students to the main issues and techniques of diffraction analysis as they relate to materials. The techniques for the experimental phase identification and determination of phase fraction via XRD will be reviewed. Topics covered include: basic X-ray physics, basic crystallography, fundamentals of XRD, XRD instrumentation and analysis techniques. (Prerequisites: ES 2001 or equivalent, and senior or graduate standing in engineering or science.) Note: Students cannot receive credit for this course if they have taken the Special Topics version of the same course (MTE 594C).

MTE 540. Analytical Methods in Materials Engineering
(3 credits)

Heat transfer and diffusion kinetics are applied to the solution of materials engineering problems. Mathematical and numerical methods for the solutions to Fourier's and Pick's laws for a variety of boundary conditions will be presented and discussed. The primary emphasis is given heat treatment and surface modification processes. Topics to be covered include solutionizing, quenching, and carburization heat treatment. (Prerequisites: ME 4840 or MTE 511 and MTE 512 or equivalent.)

MTE 550. Phase Transformations in Materials
(3 credits)

This course is intended to provide a fundamental understanding of thermodynamic and kinetic principles associated with phase transformations. The mechanisms of phase transformations will be discussed in terms of driving forces to establish a theoretical background for various physical phenomena. The principles of nucleation and growth and spinodal transformations will be described. The theoretical analysis of diffusion controlled and interface controlled growth will be presented The basic concepts of martensitic transformations will be highlighted. Specific examples will include solidification, crystallization, precipitation, sintering, phase separation and transformation toughening. (Prerequisites: MTE 511 and MTE 512, ME 4850 or equivalent.)

MTE 556/ME 5356. Smart Materials
(2 credits)

A material whose properties can respond to an external stimulus in a controlled fashion is referred to as a smart or intelligent material. These materials can be made to undergo changes modulus, shape, porosity, electrical conductivity, physical form, opacity, and magnetic properties based on an external stimulus. The stimuli can include temperature, pH, specific molecules, light, magnetic field, voltage and stress. These stimuli-sensitive materials can be utilized as sensors and as vehicles for the controlled delivery of drugs and other biomolecules in medical applications. Smart materials are also becoming important in other biological areas such as bio-separation, biosensor design, tissue engineering, protein folding, and microfluidics. The use of stimuli-sensitive materials is receiving increasing attention in the development of damage tolerant smart structures in aerospace, marine, automotive and earth quake resistant buildings. The use of smart materials is being explored for a range of applications including protective coatings, corrosion barriers, intelligent batteries, fabrics and food packaging. The purpose of this course is to provide an introduction to the various types of smart

materials including polymers, ceramic, metallic alloys and composites. Fundamental principles associated with the onset of "smart" property will be highlighted. The principles of self-healable materials based on smart materials will be discussed. The application of smart materials in various fields including sensors, actuators, diagnostics, therapeutics, packaging and other advanced applications will be presented. Note: Students cannot receive credit for this course if they have taken the Special Topics version of the same course (MTE 594).

MTE 558. Plastics
(2 credits)

This course will provide an integrated overview of the design, selection and use of synthetic plastics. The basic chemistry associated with polymerization and the structure of commercial plastics will be described. Various aspects of polymer crystallization and glass transition will be outlined. Salient aspects of fluid flow and heat transfer during the processing of plastics will be highlighted. Fundamentals of the diverse processing operations used to shape plastics and the resulting structures that develop after processing will be discussed. The mechanical behavior of plastics including elastic deformation, rubber elasticity, yielding, viscoelasticity, fracture and creep will be discussed. Plastic degradation and environmental issues associated with recycling and disposal of plastics will be examined. Typical techniques used in the analysis and testing of plastics will be described and a working knowledge of various terminologies used in commercial practice will be provided. Note: Students cannot receive credit for this course if they have taken the Special Topics version of the same course (MTE 594A).

MTE 561/ME 5361. Mechanical Behavior and Fracture of Materials
(2 credits)

The failure and wear-out mechanisms for a variety of materials (metals, ceramics, polymers, composites and microelectronics) and applications will be presented and discussed. Multi-axial failure theories and fracture mechanics will be discussed. The methodology and techniques for reliability analysis will also be presented and discussed. A materials systems approach will be used. (Prerequisites: ES 2502 and ME 3023 or equivalent, and senior or graduate standing in engineering or science.) Note: Students cannot receive credit for this course if they have taken the Special Topics version of the same course (MTE 593C/MTE 594C).

MTE 575/ME 4875. Introduction to Nanomaterials and Nanotechnology
(2 credits)

This course introduces students to current developments in nanoscale science and technology. The current advance of materials and devices constituting of building blocks of metals, semiconductors, ceramics or polymers that are nanometer size (1-100 nm) are reviewed. The profound implications for technology and science of this research field are discussed. The differences of the properties of matter on the nanometer scale from those on the macroscopic scale due to the size confinement, predominance of interfacial phenomena and quantum mechanics are studied. The main issues and techniques relevant to science and technologies on the nanometer scale are considered. New developments in this field and future perspectives are presented. Topics covered include: fabrication of nanoscale structures, characterization at nanoscale, molecular electronics, nanoscale mechanics, new architecture, nano optics and societal impacts. Recommended background: ES 2001 Introduction to Materials or equivalent

MTE 580. Materials Science and Engineering Seminar

Reports on the state-of-the-art in various areas of research and development in materials science and engineering will be presented by the faculty and outside experts. Reports on graduate student research in progress will also be required.

MTE 5816. Ceramics and Glasses for Engineering Applications
(2 credits)

This course develops an understanding of the processing, structure, property, performance relationships in crystalline and vitreous ceramics. The topics covered include crystal structure, glassy structure, phase diagrams, microstructures, mechanical properties, optical properties, thermal properties, and materials selection for ceramic materials. In addition the methods for processing ceramics for a variety of products will be included. Recommended background: ES2001 or equivalent. Note: Students cannot receive credit for this course if they have taken the Special Topics version of the same course.

MTE/MFE 5841
ME 5370. Surface Metrology
(3 credits)

This course emphasizes research applications of advanced surface metrology, including the measurement and analysis of surface roughness. Surface metrology can be important in a wide variety of situations including adhesion, friction, catalysis, heat transfer, mass transfer, scattering, biological growth, wear and wetting. These situations impact practically all the engineering disciplines and sciences. The course begins by considering basic principles and conventional analyses, and methods. Measurement and analysis methods are critically reviewed for utility. Students learn advanced methods for differentiating surface textures that are suspected of being different because of their performance or manufacture. Students will also learn methods for making correlations between surface textures and behavioral and manufacturing parameters. The results of applying these methods can be used to support the design and manufacture of surface textures, and to address issues in quality assurance. Examples of research from a broad range of applications are presented, including, food science, pavements, friction, adhesion, machining and grinding. Students do a major project of their choosing, which can involve either an in-depth literature review, or surface measurement and analysis. The facilities of WPI's Surface Metrology Laboratory are available for making measurements for selected projects. Software for advanced analysis methods is also available for use in the course. No previous knowledge of surface metrology is required. Students should have some background in engineering, math or science.

MTE 5844. Corrosion and Corrosion Control
(2 credits)

An introductory course on corrosion; aqueous corrosion, stress corrosion cracking and hydrogen effects in metals will be presented. High-temperature oxidation, carburization and sulfidation will be discussed. Discussions focus on current corrosive engineering problems and research. (Prerequisites: MTE 511 and MTE 512 or consent of the instructor.) Note: Students cannot receive credit for this course if they have taken the Special Topics version of the same course.

MTE/ME 5847. Materials for Electrochemical Energy Systems
(2 credits)

An introductory course on electrochemical engineering, fuel cells and batteries. With escalating oil prices and increasing environmental concerns, increasing attention is being paid to the development of electrochemical devices to replace traditional energy. Here several types of batteries and fuel cells will be discussed. Topics covered include: basic electrochemistry, lithium ion battery, proton exchange membrane fuel cell, solid oxide fuel cell, electrochemical method. Recommended background: ES2001 or equivalent. Note: Students cannot receive credit for this course if they have taken the Special Topics version of the same course.

MTE 594. Special Topics
(As arranged)

Theoretical or experimental studies in subjects of interest to graduate students in materials science and engineering.

Research
{As arranged)

Additional acceptable courses, 4000 series, may be found in the Undergraduate Catalog.

Mathematical Sciences

www.wpi.edu/+math

Faculty

L. Capogna, Professor and Head; Ph.D., Purdue University, 1996. Partial differential equations.

J. Abraham, Professor of Practice and Actuarial Mathematics Coordinator; Fellow, Society of Actuaries, 1991; B.S., University of Iowa, 1980.

M. Blais, Teaching Associate Professor, Coordinator of Professional Science Master's Programs and Associate Department Head; Ph.D., Cornell University, 2005. Mathematical finance.

L. Carichino, Post-Doctoral Scholar; Ph.D., Purdue University, 2016. Mathematical biology, applied mathematics, fluid-structure interaction, reduced models, multi scale coupling.

S. Cassani, Post-Doctoral Scholar; Ph.D., Purdue University, 2016. Applied mathematics, mathematical biology, numerical analysis, reduced models, multiscale models.

P. R. Christopher, Professor;. Ph.D., Clark University, 1982. Graph theory, group theory, algebraic graph theory, combinatorics, linear algebra.

W. Farr, Associate Professor; Ph.D., University of Minnesota 1986. Ordinary and partial differential equations, dynamical systems, local bifurcation theory with symmetry and its application to problems involving chemical reactions or fluid mechanics (or a combination of both).

J. D. Fehribach, Associate Professor; Ph.D., Duke University, 1985. Partial differential equations and scientific computing, free and moving boundary problems (crystal growth), nonequilibrium thermodynamics and averaging (molten carbonate fuel cells).

K. Gajamannage, Post-Doctoral Scholar; Ph.D., Clarkson University, 2016. Manifold learning, dimension reduction, pattern recognition, mathematical modelling.

J. Goulet, Teaching Professor and Coordinator, Master of Mathematics for Educators Program; Ph.D., Rensselaer Polytechnic Institute, 1976. Applications of linear algebra, cross departmental course development, project development, K-12 relations with colleges, mathematics of digital and analog sound and music.

A. C. Heinricher, Professor; Ph.D., Carnegie Mellon University, 1986. Applied probability, stochastic processes and optimal control theory.

M. Hempel, Post-Doctoral Scholar; Ph.D., ETHZ, 2015. Global geometry of graphs, polyhedra, smooth surfaces and three-manifolds.

J. Huang, Post-Doctoral Scholar; Ph.D., Tulane University, 2014. Mathematical biology, fluid dynamics, modeling simulation, scientific computing.

M. Humi, Professor; Ph.D., Weizmann Institute of Science, 1969. Mathematical physics, applied mathematics and modeling, Lie groups, differential equations, numerical analysis, turbulence and chaos.

M. Johnson, Teaching Assistant Professor; Ph.D., Clark University 2012. Industrial organization, game theory.

C. J. Larsen, Professor; Ph.D., Carnegie Mellon University, 1996. Variational problems from applications such as optimal design, fracture mechanics, and image segmentation, calculus of variations, partial differential equations, geometric measure theory, analysis of free boundaries and free discontinuity sets.

R. Y. Lui, Professor; Ph.D., University of Minnesota, 1981. Mathematical biology, partial differential equations.

K. A. Lurie, Professor; Ph.D., 1964, D.Sc., 1972, A. F. Ioffe Physical-Technical Institute, Academy of Sciences of the USSR, Russia. Control theory for distributed parameter systems, optimization and nonconvex variational calculus, optimal design.

S. M. Mallikarjunaiah, Post-Doctoral Scholar; Ph.D., Texas A&M University, 2015. Fracture mechanics, continuum mechanics, partial differential equations, finite element methods.

W. J. Martin, Professor; Ph.D., University of Waterloo, 1992. Algebraic combinatorics, applied combinatorics.

F. P. Medina, Post-Doctoral Scholar; Ph.D., Oregon State University, 2014. Absorption models, methane hydrates models, noncomplementarity constraints, applied functional analysis, numerical analysis.

U. Mosco, H. J. Gay Professor; Libera Docenza, University of Rome, 1967. Partial differential equations, convex analysis, optimal control, variational calculus, fractals.

B. Nandram, Professor; Ph.D., University of Iowa, 1989. Survey sampling theory and methods, Bayes and empirical Bayes theory and methods, categorical data analysis.

P. O'Cathain, Assistant Professor; Ph.D., National University of Ireland, Galway, 2012. Combinatorics, algebra and compressed sensing.

S. Olson, Associate Professor; Ph.D., North Carolina State University 2008. Mathematical biology, computational biofluids, scientific computing.

R. C. Paffenroth, Associate Professor; Ph.D., University of Maryland, 1999. Large scale data analytics, statistical machine learning, compressed sensing, network analysis.

H. Park, Post-Doctoral Scholar; Ph.D., Courant Institute, NYU, 2015. Financial mathematics, stochastic processes, probability, financial economics.

B. Peiris, Assistant Teaching Professor, Ph.D., Southern Illinois University, Carbondale, 2014. Bayesian Statistics, order restricted inference, meta-analysis.

J. D. Petruccelli, Professor; Ph.D., Purdue University, 1978. Time series (nonlinear models), optimal stopping (best choice problems), statistics.

B. Posterro, Teaching Assistant Professor; M.S., Financial Mathematics, Worcester Polytechnic Institute, 2010, M.S. Applied Mathematics, Worcester Polytechnic Institute, 2000.

M. Sarkis, Professor; Ph.D., Courant Institute of Mathematical Sciences, 1994. Domain decomposition methods, numerical analysis, parallel computing, computational fluid dynamics, preconditioned iterative methods for linear and non-linear problems, numerical partial differential equations, mixed and non-conforming finite methods, overlapping non-matching grids, mortar finite elements, eigenvalue solvers, aeroelasticity, porous media reservoir modeling.

B. Servatius, Professor; Ph.D., Syracuse University, 1987. Combinatorics, matroid and graph theory, structural topology, geometry, history and philosophy of mathematics.

S. Sturm, Assistant Professor; Ph.D. TU Berlin 2010. Mathematical finance: stochastic volatility, optimal portfolio problems, systemic risk; stochastic analysis: backward stochastic differential equations, large deviations, Malliavin calculus.

D. Tang, Professor; Ph.D., University of Wisconsin, 1988. Biofluids, biosolids, blood flow, mathematical modeling, numerical methods, scientific computing, nonlinear analysis, computational fluid dynamics.

B. S. Tilley, Associate Professor; Ph.D., Northwestern University, 1994. Free-boundary problems in continuum mechanics, interfacial fluid dynamics, viscous flows, partial differential equations, mathematical modeling, asymptotic methods.

B. Vernescu, Professor; Ph.D., Institute of Mathematics, Bucharest, Romania, 1989. Partial differential equations, phase transitions and free-boundaries, viscous flow in porous media, asymptotic methods and homogenization.

D. Volkov, Associate Professor; Ph.D., Rutgers University, 2001. Electromagnetic waves, inverse problems, wave propagation in waveguides and in periodic structures, electrified fluid jets.

H. F. Walker, Professor; Ph.D., Courant Institute of Mathematical Sciences, New York University, 1970. Numerical analysis, especially numerical solution of large-scale linear and nonlinear systems, unconstrained optimization, applications to ordinary and partial differential equations and statistical estimation, computational and applied mathematics.

G. Wang, Assistant Professor; Ph.D., Boston University, 2013. Stochastic control, mathematical finance, stochastic analysis, applied probability.

S. Weekes, Professor; Ph.D., University of Michigan, 1995. Numerical analysis, computational fluid dynamics, porous media flow, hyperbolic conservation laws, shock capturing schemes.

Z. Wu, Associate Professor; Ph.D., Yale University, 2009. Biostatistics, high-dimensional model selection, linear and generalized linear modeling, statistical genetics, bioinformatics.

V. Yakovlev, Research Associate; Ph.D., Institute of Radio Engineering and Electronics, Russian Academy of Sciences, 1991. Antennas for MW and MMW communications, electromagnetic fields in transmission lines and along media interfaces, control and optimization of electromagnetic and temperature fields in microwave thermal processing, issues in modeling of microwave heating, computational electromagnetics with neural networks, numerical methods, algorithms and CAD tools for RF, MW and MMW components and subsystems.

Z. Zhang, Assistant Professor; Ph.D., Brown University, 2014, Shanghai University, 2011. Numerical analysis, scientific computing, computational and applied mathematics, uncertainty qualification.

X. Zhou, Post-Doctoral Scholar; Ph.D., University of Pittsburgh, 2016. Analysis on metric spaces, nonlinear partial differential equations, sub-Riemannian geometry, differential games.

J. Zou, Assistant Professor; Ph.D., University of Connecticut, 2009. Financial time series (especially high frequency financial data), spatial statistics, biosurveillance, high dimensional statistical inference, Bayesian statistics.

Emeritus

P. W. Davis, Professor
W. J. Hardell, Professor
J. J. Malone, Professor
B. C. McQuarrie, Professor
W. B. Miller, Professor
D. Vermes, Professor

Research Interests

Active areas of research in the Mathematical Sciences Department include applied and computational mathematics, industrial mathematics, applied statistics, scientific computing, numerical analysis, ordinary and partial differential equations, non-linear analysis, electric power systems, control theory, optimal design, composite materials, homogenization, computational fluid dynamics, biofluids, dynamical systems, free and moving boundary problems, porous media modeling, turbulence and chaos, mathematical physics, mathematical biology, operations research, linear and nonlinear programming, discrete mathematics, graph theory, group theory, linear algebra, combinatorics, applied probability, stochastic processes, time series analysis, Bayesian statistics, Bayesian computation, survey research methodology, categorical data analysis, Monte Carlo methodology, statistical computing, survival analysis and model selection.

Programs of Study

The Mathematical Sciences Department offers four programs leading to the degree of master of science, a combined B.S./Master's program, a program leading to the degree of master of mathematics for educators, and a program leading to the degree of doctor of philosophy.

Master of Science in Applied Mathematics Program

This program gives students a broad background in mathematics, placing an emphasis on areas with the highest demand in applications: numerical methods and scientific computation, mathematical modeling, discrete mathematics, mathematical materials science, optimization and operations research. In addition to these advanced areas of specialization, students are encouraged to acquire breadth by choosing elective courses in other fields that complement their studies in applied mathematics. Students have a choice of completing their master's thesis or project in cooperation with one of the department's established industrial partners. The program provides a suitable foundation for the pursuit of a Ph.D. degree in applied mathematics or a related field, or for a career in industry immediately after graduation.

Master of Science in Applied Statistics Program

This program gives graduates the knowledge and experience to tackle problems of statistical design, analysis and control likely to be encountered in business, industry or academia. The program is designed to acquaint students with the theory underlying modern statistical methods, to provide breadth in diverse areas of statistics and to give students practical experience through extensive application of statistical theory to real problems.

Through the selection of elective courses, the student may choose a program with an industrial emphasis or one with a more theoretical emphasis.

Professional Master of Science in Financial Mathematics Program

This program offers an efficient, practice-oriented track to prepare students for quantitative careers in the financial industry, including banks, insurance companies, and investment and securities firms. The program gives students a solid background and sufficient breadth in the mathematical and statistical foundations needed to understand the cutting edge techniques of today and to keep up with future developments in this rapidly evolving area over the span of their careers. It also equips students with expertise in quantitative financial modeling and the computational methods and skills that are used to implement the models. The mathematical knowledge is complemented by studies in financial management, information technology and/or computer science.

The bridge from the academic environment to the professional workplace is provided by a professional master's project that involves the solution of a concrete, real-world problem directly originating in the financial industry. Students are encouraged to complete summer internships at financial firms. The department may help students to find suitable financial internships through the industrial connections of faculty affiliated with the Center for Industrial Mathematics and Statistics. Graduates of the program are expected to start or advance their professional careers in such areas as financial product development and pricing, risk management, investment decision support and portfolio management.

Professional Master of Science in Industrial Mathematics Program

This is a practice-oriented program that prepares students for successful careers in industry. The graduates are expected to be generalized problem-solvers, capable of moving from task to task within an organization. In industry, mathematicians need not only the standard mathematical and statistical modeling and computational tools, but also knowledge within other areas of science or engineering. This program aims at developing the analytical, modeling and computational skills needed by mathematicians who work in industrial environments. It also provides the breadth required by industrial multidisciplinary team environments through courses in one area of science or engineering, e.g., physics, computer science, mechanical engineering, and electrical and computer engineering.

The connection between academic training and industrial experience is provided by an industrial professional master's project that involves the solution of a concrete, real-world problem originating in industry. The department, through the industrial connections of the faculty affiliated with the Center for Industrial Mathematics and Statistics, may help students identify and select suitable industrial internships. Graduates of the program are expected to start or advance their professional careers in industry.

Master of Mathematics for Educators (MME)

This is an evening and/or online program designed primarily for secondary school mathematics teachers. Courses offer a solid foundation in areas such as geometry, algebra, modeling, discrete math and statistics, while also including the study of modern applications. Additionally, students develop materials, based on coursework, which may be used in their classes. Technology is introduced when possible to give students exposure for future consideration. Examples include Geometer's Sketchpad; Maple for algebra, calculus and graphics; Matlab for analysis of sound and music; and the TI CBL for motion and heat.

Master of Science in Mathematics for Educators (MMED)

The Master of Science in Mathematics for Educators is designed specifically for middle school, high school and junior college in-service educators. The emphasis of the program is put on mathematics content coursework combined with courses in assessment and evaluation theory and a culminating project designed by the participant. The mathematics content courses, designed for educators, offer teachers a solid foundation in areas such as geometry, algebra, modeling, discrete math and statistics, while also including the study of modern applications. In these courses, participants have the opportunity to develop materials, based on coursework, which may be used in their classes. Throughout the courses, technology is introduced whenever possible to help educators become familiar with the options available for use in the classroom. Examples of this include Geometer's Sketchpad and the TI CBL for motion and heat. This combination of content courses, assessment and evaluation theory courses, and a final project are perfect for educators looking for a program that emphasizes mathematics and supports educators in learning how to better evaluate their effectiveness in the classroom. For information about admissions and requirements, see the listing under STEM for Educators.

Doctor of Philosophy in Mathematical Sciences Program

The goal of this program is to produce active and creative problem solvers, capable of contributing in academic and industrial environments. One distinguishing feature of this program is a Ph.D. project to be completed under the guidance of an external sponsor, e.g., from industry or a national research center. The intention of this project is to connect theoretical knowledge with relevant applications and to improve skills in applying and communicating mathematics.

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Combined B.S./Master's Program

This program allows a student to work concurrently toward bachelor and master of science degrees in applied mathematics, applied statistics, financial mathematics and industrial mathematics.

Admission Requirements

A basic knowledge of undergraduate analysis, linear algebra and differential equations is assumed for applicants to the master's programs in applied mathematics and industrial mathematics. A strong background in mathematics, which should include courses in undergraduate analysis and linear algebra, is assumed for applicants to the master's program in financial mathematics. Typically, an entering student in the master of science in applied statistics program will have an undergraduate major in the mathematical sciences, engineering or a physical science; however, individuals with other backgrounds will be considered. In any case, an applicant will need a strong background in mathematics, which should include courses in undergraduate analysis and probability. Students with serious deficiencies may be required to correct them on a noncredit basis. Applicants to the Ph.D. program and those wishing to be considered for teaching assistantships should submit GRE Mathematics Subject Test scores if possible; an applicant who finds it difficult to submit a score is welcome to contact the Mathematical Sciences Department Graduate Admissions Committee (ma-questions@wpi.edu) to discuss the applicant's situation.

Candidates for the master of mathematics for educators degree must have a bachelor's degree and must possess a background equivalent to at least a minor in mathematics, including calculus, linear algebra, and statistics. Students are encouraged to enroll in courses on an ad hoc basis without official program admission. However, (at most) four such courses may be taken prior to admission.

Degree Requirements

For the M.S. in Applied Mathematics

The master's program in Applied Mathematics requires a minimum of 30 credit-hours of coursework. Additional credit from coursework may be required by the department depending on the student's background. The student's program must include at least seven MA numbered courses other than 501 or 511. Among these must be
MA 503, MA 510, and either MA 535 or MA 530. In addition, students are required to complete a Capstone Experience, which can be satisfied by one of the following options:

(a) A six credit master's thesis.
(b) A three to six credit master's project.
(c) A three credit master's practicum.
(d) A three credit research review report or research proposal.
(e) A master's exam.

The master's thesis is an original piece of mathematical research work which focuses on advancing the state of the mathematical art. The master's project consists of a creative application of mathematics to a real-world problem. It focuses on problem definition and solution using mathematical tools. The master's practicum requires a student to demonstrate the integration of advanced mathematical concepts and methods into professional practice. This could be done through a summer internship in industry or an applied research laboratory.

The remaining courses may be chosen from the graduate offerings of the Mathematical Sciences Department. Upper-level undergraduate mathematics courses or a two-course graduate sequence in another department may be taken for graduate credit, subject to the approval of the departmental Graduate Committee. Candidates are required to successfully complete the graduate seminar MA 557.

For the M.S. in Applied Statistics

The master's program in Applied Statistics requires a minimum of 30 credit-hours of coursework. Additional credit from coursework may be required by the department depending on the student's background. Courses taken must include MA 540, MA 541, MA 546, MA 547, 3 credits of MA 559 and at least three additional departmental statistics offerings: MA 509 and courses numbered 542 through 556. Students who can demonstrate a legitimate conflict in scheduling MA 559 will be assigned an alternative activity by the Mathematical Science Department Graduate Committee. In addition the student must complete a Capstone Experience, which can be satisfied by one of the following options:

(a) A six credit master's thesis.
(b) A three to six credit master's project.
(c) A three credit master's practicum.
(d) A three credit research review report or research proposal.
(e) A master's exam.

Upper-level undergraduate courses may be taken for graduate credit subject to the approval of the departmental Graduate Committee.

For the M.S. in Financial Mathematics

The master's program in Financial Mathematics requires a minimum of 30 credit-hours of coursework. Additional credit from coursework may be required by the department depending on the student's background. The curriculum consists of the following components:

1. **6 credits from required foundation courses:**
   MA 529 Stochastic Processes **or**
   MA 503 Lebesgue Measure and Integration
   MA 528 Measure Theoretic Probability Theory **or**
   MA 540 Probability and Mathematical Statistics I
2. **12 credits from core financial mathematics courses:**
   MA 571 Financial Mathematics I
   MA 572 Financial Mathematics II
   MA 573 Computational Methods of Financial Mathematics
   MA 574 Portfolio Valuation and Risk Management
   MA 575 Market and Credit Risk Topics and Management

3. **3 credits chosen from Mathematical Sciences graduate courses MA 502-590.**

   B.S./M.S. students can count undergraduate courses MA 4213 Risk Theory, MA 4214 Survival Models, MA 4235 Mathematical Optimization, MA 4237 Probabilistic Methods in Operations Research, MA 4451 Boundary Value Problems, MA 4473 Partial Differential Equations, MA 4632 Probability and Mathematical Statistics II towards electives

4. **6 credit block in one of the following complementary areas outside of the Mathematical Sciences Department: Financial Management, Information Technology, or Computer Science.**

   Students with a degree or substantial work experience in one of the above complementary areas can substitute them with other courses subject to prior approval by the graduate committee

   B.S./M.S. students can count suitable undergraduate courses towards the complementary area requirement according the number of credits of the corresponding graduate courses

   2 of the complementary area credits can be earned by taking MA 579 Financial Programming Workshop

5. **Capstone Project, which may be satisfied by one of the following options:**

   (a) A three to six credit master's project.

   (b) A three credit master's practicum.

   (c) A three credit capstone course in financial mathematics.

   The master's project consists of a creative application of mathematics to a real-world problem originating in the financial industry. It focuses on problem definition and solution using mathematical tools. The master's practicum requires a student to demonstrate the integration of advanced mathematical concepts and methods into professional practice. This could be done through an approved summer internship in industry or an applied research laboratory. The capstone course in financial mathematics can be chosen from MA 572, MA 573, MA 574, or MA 575 and will be an enhanced version of the course with extra work assigned. Prior to the start of the capstone course, a student seeking to use the course to satisfy the requirement must declare this intention to the professor of the course.

6. **MA 562A and MA 562B Professional Master's Seminar** (for no credit)

For the M.S. in Industrial Mathematics

The master's program in Industrial Mathematics requires a minimum of 30 credit-hours of coursework. Additional credit from coursework may be required by the department depending on the student's background. Students must complete four foundation courses: MA 503, MA 510 and two courses out of MA 508, MA 509, MA 529 and MA 530. Students must also complete a 12-credit-hour module composed of two courses within the department and a sequence of two courses from one graduate program outside the Mathematical Sciences Department. The department offers a wide selection of modules to suit students' interest and expertise.

In addition, students are required to complete a 3-credit-hour elective from the Mathematical Sciences Department and a 3-credit-hour master's project on a problem originating from industry. Candidates are required to successfully complete the Professional Master's Seminars MA 562A and MA 562B. The Plan of Study and the project topic require prior approval by the departmental Graduate Committee.

Examples of Modules for the M.S. Degree in Industrial Mathematics

The courses comprising the 12-credit module should form a coherent sequence that provides exposure to an area outside of mathematics and statistics, providing at the same time the mathematical tools required by that particular area. Examples of typical modules are:

- Dynamics and control module—MA 512, MA 540, ME 522 and ME 523 or ME 527;
- Materials module—MA 512, MA 526, and ME 531;
- Fluid dynamics module—MA 512, MA 526, ME 511 and ME 512 or ME 513;
- Biomedical engineering module—MA 512, MA 526, BE/ME 554 and BE/ME 558;
- Machine learning module—MA 540, MA 541, CS 509 and CS 539;
- Cryptography module—MA 533, MA 514, CS 503 and ECE 578.

For the Combined B.S./Master's Programs in Applied Mathematics and Applied Statistics

Credits from no more than four courses may be counted toward both the undergraduate and graduate degrees. All of these courses must be 4000-level or above, and at least one must be a graduate course. Three of them must be beyond the 7 units of mathematics required for the B.S. degree. Additionally, students are advised that all requirements of a particular master's program must be satisfied in order to receive the degree, and these courses should be selected accordingly.

Acceptance into the program means that the candidate is qualified for graduate school and signifies approval of the four courses to be counted for credit toward both degrees. However, in order to obtain both undergraduate and graduate credit for these courses, grades of B or better have to be obtained.

For the Master of Mathematics for Educators (M.M.E.)

Candidates for the Master of Mathematics for educators must successfully complete 30 credit hours of graduate study, including a 6-credit-hour project (see MME 592, MME 594, MME 596). This project will typically consist of a classroom study within the context of a secondary mathematics course and will be advised by faculty in the Mathematical Sciences Department. Typically, a student will enroll in 4 credit hours per semester during the fall and spring, with the remaining credit hours taken in the summer.

Students may complete the degree in as little as slightly over two years by taking two courses per semester, 3 semesters per year, and doing a project. However, the program can accommodate other completion schedules as well. The MME degree may be used to satisfy the Massachusetts Professional License requirement, provided the person holds an Initial License.

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For the Master of Science in Mathematics for Educators (MMED)

For a complete overview of degree requirements, please see STEM for Educators.

For the Ph.D.

The course of study leading to the doctor of philosophy in mathematical sciences requires the completion of at least 90 credit hours beyond the bachelor's degree or at least 60 credit hours beyond the master's degree, as follows:

General Courses (credited for students with master's degrees)	30 credits
Research Preparation Phase	24-30 credits
Research-Related Courses or Independent Studies	9-18 credits
Ph.D. Project	1-9 credits
Extra-Departmental Studies	6 credits
Dissertation Research	at least 30 credits

A brief description of other Ph.D. program requirements follows below. For further details, students are advised to consult the document *Ph.D. Program Requirements and Administrative Rules for the Department of Mathematical Sciences*, available from the departmental graduate secretary.

Within a full-time student's first semester of study (second semester for part-time students), a Plan of Study leading to the Ph.D. degree must be submitted to the departmental Graduate Committee for review and approval. The Plan of Study may subsequently be modified with review by the departmental Graduate Committee.

Extra-Departmental Studies Requirement

A student must complete at least six semester hours of courses, 500 level or higher, in WPI departments other than the Mathematical Sciences Department.

General Comprehensive Examination

A student must pass the general comprehensive examination (GCE) in order to become a Ph.D. candidate. The purpose of the GCE is to determine whether a student possesses the fundamental knowledge and skills necessary for study and research at the Ph.D. level. It is a written examination offered three times a year, once each in January, May, and August. A student must pass by January of their second year if they enter in the fall, and May of their second year if they enter in the spring.

Mathematical Sciences Ph.D. Project

A student may complete a Ph.D. project involving a problem originating with a sponsor external to the department. The purposes of the project are to broaden perspectives on the relevance and applications of mathematics and to improve skills in communicating mathematics and formulating and solving mathematical problems. Students are encouraged to work with industrial sponsors on problems involving applications of the mathematical sciences. Each Ph.D. project requires prior approval by the project advisor, the external sponsor, and the departmental Graduate Committee.

Ph.D. Preliminary Examination

Successful completion of the preliminary examination is required before a student can register for dissertation research credits. The purpose of the preliminary examination is to determine whether a student's understanding of advanced areas of mathematics is adequate to conduct independent research and successfully complete a dissertation. The preliminary examination consists of both written and oral parts. A full-time student must make the first attempt by the end of his or her third year (sixth year for part-time students) in the Ph.D. program.

Ph.D. Dissertation

The Ph.D. dissertation is a significant work of original research conducted under the supervision of a dissertation advisor, who is normally a member of the departmental faculty. The dissertation advisor chairs the student's dissertation committee, which consists of at least five members, including one recognized expert external to the department, and which must be approved by the departmental Graduate Committee. At least six months prior to completion of the dissertation, a student must submit a written dissertation proposal and present a public seminar on the research plan described in the proposal. The proposal must be approved by the dissertation committee. Upon completion of the dissertation and other program requirements, the student presents the dissertation to the dissertation committee and to the general community in a public oral defense. The dissertation committee determines whether the dissertation is acceptable.

Mathematical Sciences Computer Facilities

The Mathematical Sciences Department makes up-to-date computing equipment available for use by students in its programs.

Current facilities include a mixed environment of approximately 85 Windows, Linux/Unix and Macintosh workstations utilizing the latest in single- and dual-processor 32 and 64 bit technology. Access is available to our supercomputer, a 16 CPU SGI Altix 350. The Mathematical Sciences Department also has 3 state-of-the-art computer labs, one each dedicated to the Calculus, Statistics, and Financial Mathematics programs.

The department is continually adding new resources to give our faculty and students the tools they need as they advance in their research and studies.

Center for Industrial Mathematics and Statistics (CIMS)

www.wpi.edu/+CIMS

The Center for Industrial Mathematics and Statistics was established in 1997 to foster partnerships between the university and industry, business and government in mathematics and statistics research.

The problems facing business and industry are growing ever more complex, and their solutions often involve sophisticated mathematics. The faculty members and students associated with CIMS have the expertise to address today's complex problems and provide solutions that use relevant mathematics and statistics.

The Center offers undergraduates and graduate students the opportunity to gain real-world experience in the corporate world through projects and internships that make them more competitive in today's job market. In addition, it helps companies address their needs for mathematical solutions and enhances their technological competitiveness.

The industrial projects in mathematics and statistics offered by CIMS provide a unique education for successful careers in industry, business and higher education.

Course Descriptions

All courses are 3 credits unless otherwise noted.

Mathematical Sciences

MA 500. Basic Real Analysis

This course covers basic set theory, topology of Rn, continuous functions, uniform convergence, compactness, infinite series, theory of differentiation and integration. Other topics covered may include the inverse and implicit function theorems and Riemann-Stieltjes integration. Students may not count both MA 3831 and MA 500 toward their undergraduate degree requirements.

MA 501. Engineering Mathematics

This course develops mathematical techniques used in the engineering disciplines. Preliminary concepts will be reviewed as necessary, including vector spaces, matrices and eigenvalues. The principal topics covered will include vector calculus, Fourier transforms, fast Fourier transforms and Laplace transformations. Applications of these techniques for the solution of boundary value and initial value problems will be given. The problems treated and solved in this course are typical of those seen in applications and include problems of heat conduction, mechanical vibrations and wave propagation. (Prerequisite: A knowledge of ordinary differential equations, linear algebra and multivariable calculus is assumed.)

MA 502. Linear Algebra

This course provides an introduction to the theory and methods of applicable linear algebra. The goal is to bring out the fundamental concepts and techniques that underlie and unify the many ways in which linear algebra is used in applications. The course is suitable for students in mathematics and other disciplines who wish to obtain deeper insights into this very important subject than are normally offered in undergraduate courses. It is also intended to provide a foundation for further study in subjects such as numerical linear algebra and functional analysis.

MA 503. Lebesgue Measure and Integration

This course begins with a review of topics normally covered in undergraduate analysis courses: open, closed and compact sets; liminf and limsup; continuity and uniform convergence. Next the course covers Lebesgue measure in R^n including the Cantor set, the concept of a sigma-algebra, the construction of a nonmeasurable set, measurable functions, semicontinuity, Egorov's and Lusin's theorems, and convergence in measure. Next we cover Lebesgue integration, integral convergence theorems (monotone and dominated), Tchebyshev's inequality and Tonelli's and Fubini's theorems. Finally L^p spaces are introduced with emphasis on L^2 as a Hilbert space. Other related topics will be covered at the instructor's discretion. (Prerequisite: Basic knowledge of undergraduate analysis is assumed.)

MA 505. Complex Analysis

This course will provide a rigorous and thorough-treatment of the theory of functions of one complex variable. The topics to be covered include complex numbers, complex differentiation, the Cauchy-Riemann equations, analytic functions, Cauchy's theorem, complex integration, the Cauchy integral formula, Liouville's theorem, the Gauss mean value theorem, the maximum modulus theorem, Rouche's theorem, the Poisson integral formula, Taylor-Laurent expansions, singularity theory, conformal mapping with applications, analytic continuation, Schwarz's reflection principle and elliptic functions. (Prerequisite: knowledge of undergraduate analysis.)

MA 508. Mathematical Modeling

This course introduces mathematical model-building using dimensional analysis, perturbation theory and variational principles. Models are selected from the natural and social sciences according to the interests of the instructor and students. Examples are: planetary orbits, spring-mass systems, fluid flow, isomers in organic chemistry, biological competition, biochemical kinetics and physiological flow. Computer simulation of these models will also be considered. (Prerequisite: knowledge of ordinary differential equations and of analysis at the level of MA 501 is assumed.)

MA 509. Stochastic Modeling

This course gives students a background in the theory and methods of probability, stochastic processes and statistics for applications. The course begins with a brief review of basic probability, discrete and continuous random variables, expectations, conditional probability and basic statistical inference. Topics covered in greater depth include generating functions, limit theorems, basic stochastic processes, discrete and continuous time Markov chains, and basic queuing theory including M/M/1 and M/G/1 queues. (Prerequisite: knowledge of basic probability at the level of MA 2631 and statistics at the level of MA 2612 is assumed.) This course is offered by special arrangement only, based on expressed student interest.

MA 510/CS 522. Numerical Methods

This course provides an introduction to a broad range of modern numerical techniques that are widely used in computational mathematics, science, and engineering. It is suitable for both mathematics majors and students from other departments. It covers introductory-level material for subjects treated in greater depth in MA 512 and MA 514 and also topics not addressed in either of those courses.

Subject areas include numerical methods for systems of linear and nonlinear equations, interpolation and approximation, differentiation and integration, and differential equations. Specific topics include basic direct and iterative methods for linear systems; classical rootfinding methods; Newton's method and related methods for nonlinear systems; fixed-point iteration; polynomial, piecewise polynomial, and spline interpolation methods; least-squares approximation; orthogonal functions and approximation; basic techniques for numerical differentiation; numerical integration, including adaptive quadrature; and methods for initial-value problems for ordinary differential equations. Additional topics may be included at the instructor's discretion as time permits.

Both theory and practice are examined. Error estimates, rates of convergence, and the consequences of finite precision arithmetic are also discussed. Topics from linear algebra and elementary functional analysis will be introduced as needed. These may include norms and inner products, orthogonality and orthogonalization, operators and projections, and the concept of a function space. (Prerequisite: knowledge of undergraduate linear algebra and differential equations is assumed, as is familiarity with MATLAB or a higher-level programming language.)

MA 511. Applied Statistics for Engineers and Scientists

This course is an introduction to statistics for graduate students in engineering and the sciences. Topics covered include basic data analysis, issues in the design of studies, an introduction to probability, point and interval estimation and hypothesis testing for means and proportions from one and two samples, simple and multiple regression, analysis of one and two-way tables, one-way analysis of variance. As time permits, additional topics, such as distribution-free methods and the design and analysis of factorial studies will be considered. (Prerequisites: Integral and differential calculus.)

MA 512. Numerical Differential Equations

This course begins where MA 510 ends in the study of the theory and practice of the numerical solution of differential equations. Central topics include a review of initial value problems, including Euler's method, Runge-Kutta methods, multi-step methods, implicit methods and predictor-corrector methods; the solution of two-point boundary value problems by shooting methods and by the discretization of the original problem to form systems of nonlinear equations; numerical stability; existence and uniqueness of solutions; and an introduction to the solution of partial differential equations by finite differences. Other topics might include finite element or boundary element methods, Galerkin methods, collocation, or variational methods. (Prerequisites: graduate or undergraduate numerical analysis. Knowledge of a higher-level programming language is assumed.)

MA 514. Numerical Linear Algebra

This course provides students with the skills necessary to develop, analyze and implement computational methods in linear algebra. The central topics include vector and matrix algebra, vector and matrix norms, the singular value decomposition, the LU and QR decompositions, Householder transformations and Givens rotations, and iterative methods for solving linear systems including Jacobi, Gauss-Seidel, SOR and conjugate gradient methods; and eigenvalue

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problems. Applications to such problem areas as least squares and optimization will be discussed. Other topics might include: special linear systems, such as symmetric, positive definite, banded or sparse systems; preconditioning; the Cholesky decomposition; sparse tableau and other least-square methods; or algorithms for parallel architectures. (Prerequisite: basic knowledge of linear algebra or equivalent background. Knowledge of a higher-level programming language is assumed.)

MA 520. Fourier Transforms and Distributions

The course will cover L^1, L^2, L^∞ and basic facts from Hilbert space theory (Hilbert basis, projection theorems, Riesz theory). The first part of the course will introduce Fourier series: the L^2 theory, the C^∞ theory: rate of convergence, Fourier series of real analytic functions, application to the trapezoidal rule, Fourier transforms in L^1, Fourier integrals of Gaussians, the Schwartz class S, Fourier transforms and derivatives, translations, convolution, Fourier transforms in L^2, and characteristic functions of probability distribution functions. The second part of the course will cover tempered distributions and applications to partial differential equations. Other related topics will be covered at the instructor's discretion. (Prerequisite: MA 503.)

MA 521. Partial Differential Equations

This course considers a variety of material in partial differential equations (PDE). Topics covered will be chosen from the following: classical linear elliptic, parabolic and hyperbolic equations and systems, characteristics, fundamental/Green's solutions, potential theory, the Fredholm alternative, maximum principles, Cauchy problems, Dirichlet/Neumann/Robin problems, weak solutions and variational methods, viscosity solutions, nonlinear equations and systems, wave propagation, free and moving boundary problems, homogenization. Other topics may also be covered. (Prerequisites: MA 503 or equivalent.)

MA 522. Hilbert Spaces and Applications to PDE

The course covers Hilbert space theory with special emphasis on applications to linear ODs and PDEs. Topics include spectral theory for linear operators in n-dimensional and infinite dimensional Hilbert spaces, spectral theory for symmetric compact operatos, linear and bilinear forms, Riesz and Lax-Milgram theorems, weak derivatives, Sobolev spaces H^1, H^2, Rellich compactness theorem, weak and classical solutions for Dirichlet and Neumann problems in one variable and in Rn, Dirichlet variational principle, eigenvalues and eigenvectors. Other related topics will be covered at the instructor's discretion. (Prerequisite: MA 503.)

MA 524. Convex Analysis and Optimization

This course covers topics in functional analysis that are critical to the study of convex optimization problems. The first part of the course will include the minimization theory for quadratic and convex functionals on convex sets and cones, the Legendre-Fenchel duality, variational inequalities and complementarity systems. The second part will include optimal stopping time problems in deterministic control, value functions and Hamilton-Jacobi inequalities and linear and quadratic programming, duality and Kuhn-Tucker multipliers. Other related topics will be covered at the instructor's discretion. (Prerequisite: MA 503.)

MA 525. Optimal Control and Design with Composite Materials I

Modern technology involves a wide application of materials with internal structure adapted to environmental demands. This, the first course in a two-semester sequence, will establish a theoretical basis for identifying structures that provide optimal response to prescribed external factors. Material covered will include basics of the calculus of variations: Euler equations; transversality conditions; Weierstrass-Erdmann conditions for corner points; Legendre, Jacobi and Weierstrass conditions; Hamiltonian form of the necessary conditions; and Noether's theorem. Pontryagin's maximum principle in its original lumped parameter form will be put forth as well as its distributed parameter extension. Chattering regimes of control and relaxation through composites will be introduced at this point. May be offered by special arrangement.

MA 526. Optimal Control and Design with Composite Materials II

Topics presented will include basics of homogenization theory. Bounds on the effective properties of composites will be established using the translation method and Hashin-Shtrikman variational principles. The course concludes with a number of examples demonstrating the use of the theory in producing optimal structural designs. The methodology given in this course turns the problem of optimal design into a problem of rigorous mathematics. This course can be taken independently or as the sequel to MA 525.

MA 528. Measure Theoretic Probability Theory

This course is designed to give graduate students interested in financial mathematics and stochastic analysis the necessary background in measure-theoretic probability and provide a theoretical foundation for Ph.D. students with research interests in analysis and mathematical statistics. Besides classical topics such as the axiomatic foundations of probability, conditional probabil-ities and independence, random variables and their distributions, and limit theorems, this course focuses on concepts crucial for the understanding of stochastic processes and quantitative finance: conditional expectations, filtrations and martingales as well as change of measure techniques and the Radon-Nikodym theorem. A wide range of illustrative examples from a topic chosen by the instructor's discretion (e.g financial mathematics, signal processing, actuarial mathematics) will be presented. (Prerequisite: MA 500 Basic Real Analysis or equivalent.)

MA 529. Stochastic Processes

This course is designed to introduce students to continuous-time stochastic processes. Stochastic processes play a central role in a wide range of applications from signal processing to finance and also offer an alternative novel viewpoint to several areas of mathematical analysis, such as partial differential equations and potential theory. The main topics for this course are martingales, maximal inequalities and applications, optimal stopping and martingale convergence theorems, the strong Markov property, stochastic integration, Ito's formula and applications, martingale representation theorems, Girsanov's theorem and applications, and an introduction to stochastic differential equations, the Feynman-Kac formula, and connections to partial differential equations. Optional topics (at the instructor's discretion) include Markov processes and Poisson-and jump-processes. (Prerequisite: MA 528. Measure-Theoretic Probability Theory, which can be taken concurrently (or, with special permission by the instructor, MA 540)).

MA 530. Discrete Mathematics

This course provides the student of mathematics or computer science with an overview of discrete structures and their applications, as well as the basic methods and proof techniques in combinatorics. Topics covered include sets, relations, posets, enumeration, graphs, digraphs, monoids, groups, discrete probability theory and propositional calculus. (Prerequisites: college math at least through calculus. Experience with recursive programming is helpful, but not required.)

MA 533. Discrete Mathematics II

This course is designed to provide an in-depth study of some topics in combinatorial mathematics and discrete optimization. Topics may vary from year to year. Topics covered include, as time permits, partially ordered sets, lattices, matroids, matching theory, Ramsey theory, discrete programming problems, computational complexity of algorithms, branch and bound methods.

MA 535. Algebra

Fundamentals of group theory: homomorphisms and the isomorphism theorems, finite groups, structure of finitely generated Abelian groups. Structure of rings: homomorphisms, ideals, factor rings and the isomorphism theorems, integral domains, factorization. Field theory: extension fields, finite fields, theory of equations. Selected topics from: Galois theory, Sylow theory, Jordan-Hölder theory, Polya theory, group presentations, basic representation theory and group characters, modules. Applications chosen from mathematical physics, Gröbner bases, symmetry, cryptography, error-correcting codes, number theory.

MA 540/4631. Probability and Mathematical Statistics I

Intended for advanced undergraduates and beginning graduate students in the mathematical sciences, and for others intending to pursue the mathematical study of probability and statistics. Topics covered include axiomatic foundations, the calculus of probability, conditional probability and independence, Bayes' Theorem, random variables, discrete and continuous distributions, joint, marginal and conditional distributions, covariance and correlation, expectation, generating functions, exponential families, transformations of random variables, types of convergence, laws of large numbers the Central Limit Theorem, Taylor series expansion, the delta method. (Prerequisite: knowledge of basic probability at the level of MA 2631 and of advanced calculus at the level of MA 3831/3832 is assumed.)

MA 541/4632. Probability and Mathematical Statistics II

This course is designed to provide background in principles of statistics. Topics covered include estimation criteria: method of moments, maximum likelihood, least squares, Bayes, point and interval estimation, Fisher's information, Cramer-Rao lower bound, sufficiency, unbiasedness, and completeness, Rao-Blackwell Theorem, efficiency, consistency, interval estimation pivotal quantities, Neyman-Person Lemma, uniformly most powerful tests, unbiased, invariant and similar tests, likelihood ratio tests, convex loss functions, risk functions, admissibility and minimaxity, Bayes decision rules. (Prerequisite: knowledge of the material in MA 540 is assumed.)

MA 542. Regression Analysis

Regression analysis is a statistical tool that utilizes the relation between a response variable and one or more predictor variables for the purposes of description, prediction and/or control. Successful use of regression analysis requires an appreciation of both the theory and the practical problems that often arise when the technique is employed with real-world data. Topics covered include the theory and application of the general linear regression model, model fitting, estimation and prediction, hypothesis testing, the analysis of variance and related distribution theory, model diagnostics and remedial measures, model building and validation, and generalizations such as logistic response models and Poisson regression. Additional topics may be covered as time permits. Application of theory to real-world problems will be emphasized using statistical computer packages. (Prerequisite: knowledge of probability and statistics at the level of MA 511 and of matrix algebra is assumed.)

MA 543/DS 502. Statistical Methods for Data Science

Statistical Methods for Data Science surveys the statistical methods most useful in data science applications. Topics covered include predictive modeling methods, including multiple linear regression, and time series, data dimension reduction, discrimination and classification methods, clustering methods, and committee methods. Students will implement these methods using statistical software. Prerequisites: Statistics at the level of MA 2611 and MA 2612 and linear algebra at the level of MA 2071.

MA 546. Design and Analysis of Experiments

Controlled experiments—studies in which treatments are assigned to observational units—are the gold standard of scientific investigation. The goal of the statistical design and analysis of experiments is to (1) identify the factors which most affect a given process or phenomenon; (2) identify the ways in which these factors affect the process or phenomenon, both individually and in combination; (3) accomplish goals 1 and 2 with minimum cost and maximum efficiency while maintaining the validity of the results. Topics covered in this course include the design, implementation and analysis of completely randomized complete block, nested, split plot, Latin square and repeated measures designs. Emphasis will be on the application of the theory to real data using statistical computer packages. (Prerequisite: knowledge of basic probability and statistics at the level of MA 511 is assumed.)

MA 547. Design and Analysis of Observational and Sampling Studies

Like controlled experiments, observational studies seek to establish cause-effect relationships, but unlike controlled experiments, they lack the ability to assign treatments to observational units. Sampling studies, such as sample surveys, seek to characterize aspects of populations by obtaining and analyzing samples from those populations. Topics from observational studies include: prospective and retrospective studies; overt and hidden bias; adjustments by stratification and matching. Topics from sampling studies include: simple random sampling and associated estimates for means, totals, and proportions; estimates for subpopulations; unequal probability sampling; ratio and regression estimation; stratified, cluster, systematic, multistage, double sampling designs, and, time permitting, topics such as model-based sampling, spatial and adaptive sampling. (Prerequisite: knowledge of basic probability and statistics, at the level of MA 511 is assumed.)

MA 548. Quality Control

This course provides the student with the basic statistical tools needed to evaluate the quality of products and processes. Topics covered include the philosophy and implementation of continuous quality improvement methods, Shewhart control charts for variables and attributes, EWMA and Cusum control charts, process capability analysis, factorial and fractional factorial experiments for process design and improvement, and response surface methods for process optimization. Additional topics will be covered as time permits. Special emphasis will be placed on realistic applications of the theory using statistical computer packages. (Prerequisite: knowledge of basic probability and statistic, at the level of MA 511 is assumed.)

MA 549. Analysis of Lifetime Data

Lifetime data occurs frequently in engineering, where it is known as reliability or failure time data, and in the biomedical sciences, where it is known as survival data. This course covers the basic methods for analyzing such data. Topics include: probability models for lifetime data, censoring, graphical methods of model selection and analysis, parametric and distribution-free inference, parametric and distribution-free regression methods. As time permits, additional topics such as frailty models and accelerated life models will be considered. Special emphasis will be placed on realistic applications of the theory using statistical computer packages. (Prerequisite: knowledge of basic probability and statistics at the level of MA 511 is assumed.)

MA 550. Time Series Analysis

Time series are collections of observations made sequentially in time. Examples of this type of data abound in many fields ranging from finance to engineering. Special techniques are called for in order to analyze and model these data. This course introduces the student to time and frequency domain techniques, including topics such as autocorrelation, spectral analysis, and ARMA and ARIMA models, Box-Jenkins methodology, fitting, forecasting, and seasonal adjustments. Time permitting, additional topics will be chosen from: Kalman filter, smoothing techniques, Holt-Winters procedures, FARIMA and GARCH models, and joint time-frequency methods such as wavelets. The emphasis will be in application to real data situations using statistical computer packages. (Prerequisite: knowledge of MA 511 is assumed. Knowledge of MA 541 is also assumed, but may be taken concurrently.)

MA 552. Distribution-Free and Robust Statistical Methods

Distribution-free statistical methods relax the usual distributional modeling assumptions of classical statistical methods. Robust methods are statistical procedures that are relatively insensitive to departures from typical assumptions, while retaining the expected behavior when assumptions are satisfied. Topics covered include, time permitting, order statistics and ranks; classical distribution-free tests such as the sign, Wilcoxon signed rank, and Wilcoxon rank sum tests, and associated point estimators and confidence intervals; tests pertaining to one and two-way layouts; the Kolmogorov-Smirnov test; permutation methods; bootstrap and Monte Carlo methods; M, L, and R estimators, regression, kernel density estimation and other smoothing methods. Comparisons will be made to standard parametric methods. (Prerequisite: knowledge of MA 541 is assumed, but may be taken concurrently.)

MA 554. Applied Multivariate Analysis

This course is an introduction to statistical methods for analyzing multivariate data. Topics covered are multivariate sampling distributions, tests and estimation of multivariate normal parameters, multivariate ANOVA, regression, discriminant analysis, cluster analysis, factor analysis and principal components. Additional

topics will be covered as time permits. Students will be required to analyze real data using one of the standard packages available. (Prerequisite: knowledge of MA 541 is assumed, but may be taken concurrently. Knowledge of matrix algebra is assumed.)

MA 556. Applied Bayesian Statistics

Bayesian statistics makes use of an inferential process that models data summarizing the results in terms of probability distributions for the model parameters. A key feature is that in the Bayesian approach, past information can be updated with new data in an elegant way in order to aid in decision making. Topics included in the courses: statistical decision theory, the Bayesian inferential framework (model specification, model fitting and model checking); computational methods for posterior simulation integration; regression models, hierarchical models, and ANOVA; time permitting, additional topics will include generalized linear models, multivariate models, missing data problems, and time series analysis. (Prerequisites: knowledge of MA 541 is assumed.)

MA 557 Graduate Seminar in Analysis and Applied Mathematics

(1 credit)

This seminar introduces students to modern issues in Analysis and Applied Mathematics. During the seminar, students and faculty will present and discuss recent research papers from the literature. Students will gain insights about current advances In the mathematical sciences and their applications.

MA 559. Statistics Graduate Seminar

(1 credit)

This seminar introduces students to issues and trends in modern statistics. In the seminar, students and faculty will read and discuss survey and research papers, make and attend presentations, and participate in brainstorming sessions toward the solution of advanced statistical problems.

MA 560. Graduate Seminar

(0 credits)

Designed to introduce graduate students to study of original papers and afford them opportunity to give account of their work by talks in the seminar.

MA 562 A and B. Professional Master's Seminar

(0 credits)

This seminar will introduce professional master's students to topics related to general writing, presentation, group communication and interviewing skills, and will provide the foundations to successful cooperation within interdisciplinary team environments. All full-time students will be required to take both components A and B of the seminar during their professional master's studies.

MA 571. Financial Mathematics I

This course provides an introduction to many of the central concepts in mathematical finance. The focus of the course is on arbitrage-based pricing of derivative securities. Topics include stochastic calculus, securities markets, arbitrage-based pricing of options and their uses for hedging and risk management, forward and futures contracts, European options, American options, exotic options, binomial stock price models, the Black-Scholes-Merton partial differential equation, risk-neutral option pricing, the fundamental theorems of asset pricing, sensitivity measures ("Greeks"), and Merton's credit risk model. (Prerequisite: MA 540, which can be taken concurrently.)

MA 572. Financial Mathematics II

The course is devoted to the mathematics of fixed income securities and to the financial instruments and methods used to manage interest rate risk. The first topics covered are the term-structure of interest rates, bonds, futures, interest rate swaps and their uses as investment or hedging tools and in asset-liability management. The second part of the course is devoted to dynamic term-structure models, including risk-neutral interest rate trees, the Heath-Jarrow-Morton model, Libor market models, and forward measures. Applications of these models are also covered, including the pricing of non-linear interest rate derivatives such as caps, floors, collars, swaptions and the dynamic hedging of interest rate risk. The course concludes with the coverage of mortgage-backed and asset-backed securities. (Prerequisite: MA 571.)

MA 573. Computational Methods of Financial Mathematics

Most realistic quantitative finance models are too complex to allow explicit analytic solutions and are solved by numerical computational methods. The first part of the course covers the application of finite difference methods to the partial differential equations and interest rate models arising in finance. Topics included are explicit, implicit and Crank-Nicholson finite difference schemes for fixed and free boundary value problems, their convergence and stability. The second part of the course covers Monte Carlo simulation methods, including random number generation, variance reduction techniques and the use of low discrepancy sequences. (Prerequisites: MA 571 and programming skills at the level of MA 579, which can be taken concurrently.)

MA 574. Portfolio Valuation and Risk Management

Balancing financial risks vs returns by the use of asset diversification is one of the fundamental tasks of quantitative financial management. This course is devoted to the use of mathematical optimization and statistics to allocate assets, to construct and manage portfolios and to measure and manage the resulting risks. The fist part of the course covers Markowitz's mean-variance optimization and efficient frontiers, Sharpe's single index and capital asset pricing models, arbitrage pricing theory, structural and statistical multi-factor models, risk allocation and risk budgeting. The second part of the course is devoted to the intertwining of optimization and statistical methodologies in modern portfolio management, including resampled efficiency, robust and Bayesian statistical methods, the Black-Litterman model and robust portfolio optimization.

MA 575. Market and Credit Risk Models and Management

The objective of the course is to familiarize students with the most important quantitative models and methods used to measure and manage financial risk, with special emphasis on market and credit risk. The course starts with the introduction of metrics of risk such as volatility, value-at-risk and expected shortfall and with the fundamental quantitative techniques used in financial risk evaluation and management. The next section is devoted to market risk including volatility modeling, time series, non-normal heavy tailed phenomena and multivariate notions of codependence such as copulas, correlations and tail-dependence. The final section concentrates on credit risk including structural and dynamic models and default contagion and applies the mathematical tools to the valuation of default contingent claims including credit default swaps, structured credit portfolios and collateralized debt obligations. (Prerequisite: knowledge of MA 540 assumed but can be taken concurrently.)

MA 579. Financial Programming Workshop

(1 or 2 credits)

The objective is to elevate the students' computer programming skills to the semi-professional level required in quantitative finance. Participants learn through hands-on experience by working on a structured set of mini projects from computational finance under the guidance of an experienced trainer and the faculty in charge. The programming language used may be C++, MATLAB, R/S, VB or another language widely used in quantitative finance and may alternate from year to year. (Prerequisite: Intermediate scientific programming skills.)

MA 584/BCB 504. Statistical Methods in Genetics and Bioinformatics

This course provides students with knowledge and understanding of the applications of statistics in modern genetics and bioinformatics. The course generally covers population genetics, genetic epidemiology, and statistical models in bioinformatics. Specific topics include meiosis modeling, stochastic models for recombination, linkage and association studies (parametric vs. nonparametric models, family-based vs. population-based models) for mapping genes of qualitative and quantitative traits, gene expression data analysis, DNA and protein sequence analysis, and molecular evolution. Statistical approaches include log-likelihood ratio tests, score tests, generalized linear models, EM algorithm, Markov chain Monte Carlo, hidden Markov model, and classification and regression trees. Students may not receive credit for both MA 584 and MA 4603. (Prerequisite: knowledge of probability and statistics at the undergraduate level.)

MA 590. Special Topics

Courses on special topics are offered under this number. Contact the Mathematical Sciences Department for current offerings.

MA 595. Independent Study

(1 to 3 credits)

Supervised independent study of a topic of mutual interest to the instructor and the student.

MA 596. Master's Capstone

(1 or more credits)

The Master's Capstone is designed to integrate classroom learning with real-world practice. It can consist of a project, a practicum, a research review report or a research proposal. A written report and a presentation are required.

MA 598. Professional Master's Project

(1 or more credits)

This project will provide the opportunity to apply and extend the material studied in the coursework to the study of a real-world problem originating in the industry. The project will be a capstone integrating industrial experience with the previously acquired academic knowledge and skills. The topic of the project will come from a problem generated in industry, and could originate from prior internship or industry experience of the student. The student will prepare a written project report and make a presentation before a committee including the faculty advisor, at least one additional WPI faculty member and representatives of a possible industrial sponsor. The advisor of record must be a faculty member of the WPI Mathematical Sciences Department. The student must submit a written project proposal for approval by the Graduate Committee prior to registering for the project.

MA 599. Thesis

(1 or more credits)

Research study at the master's level.

MA 698. Ph.D. Project

(1 or more credits)

Ph.D. project work.

MA 699. Dissertation

(1 or more credits)

Research study at the Ph.D. level.

Mathematics for Educators

MME 518. Geometrical Concepts

This course focuses primarily on the foundations and applications of Euclidean and non-Euclidean geometries. The rich and diverse nature of the subject also implies the need to explore other topics, for example, chaos and fractals. The course incorporates collaborative learning and the investigation of ideas through group projects. Possible topics include geometrical software and computer graphics, tiling and tessellations, two- and three-dimensional geometry, inversive geometry, graphical representations of functions, model construction, fundamental relationship between algebra and geometry, applications of geometry, geometry transformations and projective geometry, and convexity.

MME 522. Applications of Calculus

(2 credits)

There are three major goals for this course: to establish the underlying principles of calculus, to reinforce students' calculus skills through investigation of applications involving those skills, and to give students the opportunity to develop projects and laboratory assignments for use by first-year calculus students. The course will focus heavily on the use of technology to solve problems involving applications of calculus concepts. In addition, MME students will be expected to master the mathematical rigor of these calculus concepts so that they will be better prepared to develop their own projects and laboratory assignments. For example, if an MME student chose to develop a lab on convergence of sequence, he/she would be expected to understand the rigorous definition of convergence and how to apply it to gain sufficient and/or necessary conditions for convergence. The process of developing these first-year calculus assignments will enable the MME students to increase their own mathematical understanding of concepts while learning to handle mathematical and computer issues which will be encountered by their own calculus students. Their understanding of the concepts and applications of calculus will be further reinforced through computer laboratory assignments and group projects. Applications might include exponential decay of drugs in the body, optimal crankshaft design, population growth, or development of cruise control systems. (Prerequisite: MME 532)

MME 523. Analysis with Applications

(2 credits)

This course introduces students to mathematical analysis and its use in modeling. It will emphasize topics of calculus (including multidimensional) in a rigorous way. These topics will be motivated by their usefulness for understanding concepts of the calculus and for facilitating the solutions of engineering and science problems. Projects involving applications and appropriate use of technology will be an essential part of the course. Topics covered may include dynamical systems and differential equations; growth and decay; equilibrium; probabilistic dynamics; optimal decisions and reward; applying, building and validating models; functions on n-vectors; properties of functions; parametric equations; series; applications such as pendulum problems; electromagnetism; vibrations; electronics; transportation; gravitational fields; and heat loss. (Prerequisite: MME 532)

MME/SEME 524-25. Probability, Statistics and Data Analysis I, II

(4 credits)

This course introduces students to probability, the mathematical description of random phenomena, and to statistics, the science of data. Students in this course will acquire the following knowledge and skills:

- Probability models-mathematical models used to describe and predict random phenomena. Students will learn several basic probability models and their uses, and will obtain experience in modeling random phenomena.
- Data analysis-the art/science of finding patterns in data and using those patterns to explain the process which produced the data. Students will be able to explore and draw conclusions about data using computational and graphical methods. The iterative nature of statistical exploration will be emphasized.
- Statistical inference and modeling-the use of data sampled from a process and the probability model of that process to draw conclusions about the process. Students will attain proficiency in selecting, fitting and criticizing models, and in drawing inference from data.
- Design of experiments and sampling studies – the proper way to design experiments and sampling studies so that statistically valid inferences can be drawn. Special attention will be given to the role of experiments and sampling studies in scientific investigation. Through lab and project work, students will obtain practical skills in designing and analyzing studies and experiments. Course topics will be motivated whenever possible by applications and reinforced by experimental and computer lab experiences. One in-depth project per semester involving design, data collection, and statistical or probabilistic analysis will serve to integrate and consolidate student skills and understanding. Students will be expected to learn and use a statistical computer package such as MINITAB.

MME 526-27. Linear Models I, II

(4 credits)

This two-course sequence imparts computational skills, particularly those involving matrices, to deepen understanding of mathematical structure and methods of proof; it also includes discussion on a variety of applications of the material developed, including linear optimization. Topics in this sequence may include systems of linear equations, vector spaces, linear independence, bases, linear transformations, determinants, eigenvalues and eigenvectors, systems of linear inequalities, linear programming problems, basic solutions, duality and game theory. Applications may include economic models, computer graphics, least squares approximation, systems of differential equations, graphs and networks, and Markov processes. (Prerequisite: MME 532)

MME 528. Mathematical Modeling and Problem Solving
(2 credits)

This course introduces students to the process of developing mathematical models as a means for solving real problems. The course will encompass several different modeling situations that utilize a variety of mathematical topics. The mathematical fundamentals of these topics will be discussed, but with continued reference to their use in finding the solutions to problems. Problems to be covered include balance in small group behavior, traffic flow, air pollution flow, group decision making, transportation, assignment, project planning and the critical path method, genetics, inventory control and queueing. (Prerequisite: MME 532)

MME 529. Numbers, Polynomials and Algebraic Structures
(2 credits)

This course enables secondary mathematics teachers to see how commonly taught topics such as number systems and polynomials fit into the broader context of algebra. The course will begin with treatment of arithmetic, working through Euclid's algorithm and its applications, the fundamental theorem of arithmetic and its applications, multiplicative functions, the Chinese remainder theorem and the arithmetic of Z/n. This information will be carried over to polynomials in one variable over the rational and real numbers, culminating in the construction of root fields for polynomials via quotients of polynomial rings. Arithmetic in the Gaussian integers and the integers in various other quadratic fields (especially the field of cube roots of unity) will be explored through applications such as the generation of Pythagorean triples and solutions to other Diophantine equations (like finding integer-sided triangles with a 60 degree angle). The course will then explore cyclotomy, and the arithmetic in rings of cyclotomic integers. This will culminate in Gauss's construction of the regular 5-gon and 17-gon and the impossibility of constructing a 9-gon or trisecting a 60-degree angle. Finally, solutions of cubics and quartics by radicals will be studied. All topics will be based on the analysis of explicit calculations with (generalized) numbers. The proposed curriculum covers topics that are part of the folklore for high school mathematics (the impossibility of certain ruler and compass constructions), but that many teachers know only as facts. There are also many applications of the ideas that will allow the teachers to use results and ideas from abstract algebra to construct for their students problems that have manageable solutions.

MME 531. Discrete Mathematics
(3 credits)

This course deals with concepts and methods which emphasize the discrete nature in many problems and structures. The rapid growth of this branch of mathematics has been inspired by its wide range of applicability to diverse fields such as computer science, management, and biology. The essential ingredients of the course are:

Combinatorics -The Art of Counting. Topics include basic counting principles and methods such as recurrence relations, generating functions, the inclusion-exclusion principle and the pigeon-hole principle. Applications may include block designs, latin squares, finite projective planes, coding theory, optimization and algorithmic analysis.

Graph Theory. This includes direct graphs and networks. Among the parameters to be examined are traversibility, connectivity, planarity, duality and colorability.

MME 532. Differential Equations
(2 credits)

This course would have concepts and techniques for both Ordinary and Partial Differential Equations. Topics from ordinary differential equations include existence and uniqueness for first order, single variable problems as well as separation of variables and linear methods for first order problems. Second order, linear equations would be solved for both the homogeneous and non homogeneous cases. The phenomena of beats and resonance would be analyzed. The Laplace Transform would be introduced for appropriate second order nonhomogeneous problems. Partial Differential Equations would focus on boundary value problems arising from the Heat and Wave equations in one variable. Fourier Series expansions would be used to satisfy initial conditions and the concepts of orthogonality and convergence addressed.

MME 592/SEME 602. Project Preparation (Part of a 3-course sequence with MME 594 and MME 596)
(2 credits) (ISG)

Students will research and develop a mathematical topic or pedagogical technique. The project will typically lead to classroom implementation; however, a project involving mathematical research at an appropriate level of rigor will also be acceptable. Preparation will be completed in conjunction with at least one faculty member from the Mathematical Sciences Department and will include exhaustive research on the proposed topic. The course will result in a detailed proposal that will be presented to the MME Project Committee for approval; continuation with the project is contingent upon this approval.

MME 594/SEME 604. Project Implementation
(2 credits) (ISG)

Students will implement and carry out the project developed during the project preparation course. Periodic contact and/or observations will be made by the project advisor (see MME 592 Project Preparation) in order to provide feedback and to ensure completion of the proposed task. Data for the purpose of evaluation will be collected by the students throughout the term, when appropriate. If the project includes classroom implementation, the experiment will last for the duration of a semester.

MME 596/SEME 606. Project Analysis and Report
(2 credits) (ISG)

Students will complete a detailed statistical analysis of any data collected during the project implementation using techniques from MME 524-525 Probability, Statistics, and Data Analysis. The final report will be a comprehensive review of the relevant literature, project description, project implementation, any statisical results and conclusions. Project reports will be subject to approval by the MME Project committee and all students will be required to present their project to the mathematical sciences faculty. Course completion is contingent upon approval of the report and satisfactory completion of the presentation.

Mechanical Engineering

www.me.wpi.edu

Faculty

J. Yagoobi, George I. Alden Professor and Department Head; Ph.D., University of Illinois at Champaign-Urbana, 1984. Enhancement of heat transfer in macro, micro, and nano-scales, liquid vapor phase change, electrohydrodynamics, impinging jets, drying

D. Apelian, Howmet Professor, Director of the Metals Processing Institute; Sc.D., Massachusetts Institute of Technology, 1972. Solidification processing, spray casting, molten metal processing, aluminum foundry processing, plasma processing and knowledge engineering in materials processing

H. K. Ault, Associate Professor; Ph.D., Worcester Polytechnic Institute, 1988. Geometric modeling, mechanical design, CAD, kinematics, biomechanics and rehabilitation engineering

I. Bar-On, Professor; Ph.D., Hebrew University of Jerusalem, 1984. Clean energy, economic impact of alternative energy systems, fuel cell technology, cost modeling, fatigue and fracture of ceramics, metals and composites

J. J. Blandino, Associate Professor; Ph.D. California Institute of Technology, 2001. Fluid mechanics and heat transfer in microdevices, plasma diagnostics, electric and chemical propulsion, propulsion system design for precision formation flying

C. A. Brown, Professor, Director Surface Metrology Laboratory; Ph.D., University of Vermont, 1983. Surface metrology, multi-scale geometric analyses, axiomatic design, sports engineering, and manufacturing processes

R. V. Cowlagi, Assistant Professor, Ph.D., Georgia Institute of Technology, 2011. Control of autonomous systems with complex capabilities

M. A. Demetriou, Professor; Ph.D., University of Southern California, 1993. Control of intelligent systems, control of fluid-structure interaction systems, fault detection and accommodation of dynamical systems, acoustic and vibration control, smart materials and structures, sensor and actuator networks in distributed processes, control of mechanical systems

C. Demetry, Associate Professor; Ph.D., Massachusetts Institute of Technology, 1993. Pedagogical research, materials science and engineering education, educational technology, outcomes of K-12 outreach, nanocrystalline materials

M. F. Dimentberg, Professor; Ph.D., Moscow Institute of Power Engineering, 1963. Applied mechanics, random vibrations, nonlinear dynamics, rotordynamics, mechanical signature analysis, stochastic mechanics

G. Fischer, Associate Professor, Ph.D., Johns Hopkins University, 2008. Medical robotics, computer assisted surgery, robot control, automation, sensors and actuators

M. S. Fofana, Associate Professor, Ph.D., University of Waterloo, Waterloo, Canada, 1993. Nonlinear delay dynamical systems, stochastic bifurcations, regenerative chatter, numerically controlled CAD/CAM machining, vehicle ambulance reliability design and technology, systems engineering analysis, reduction of treatment delays in kidney dialysis, medical and public health engineering, emergency and disaster response robots

C. Furlong, Associate Professor; Ph.D., WPI, 1999. MEMS and MOEMS, nanotechnology, mechatronics, laser applications, holography, computer modeling of dynamic systems

N. A. Gatsonis, Director, Aerospace Engineering Program; Ph.D., Massachusetts Institute of Technology, 1991. Development of numerical simulation methods and modeling of nonequilibrium, multi-component, multi-scale, gaseous and plasma flows; continuum/atomistic simulation of macro-, micro- and nano-scale fluid transport processes, development of plasma diagnostics and microfluidic devices, spacecraft propulsion and micro-propulsion; spacecraft/environment interactions

S. I. Guceri, Professor, Ph.D., North Carolina State University, 1976. Rapid fabrication, rapid prototyping, layered manufacturing, additive manufacturing, laser manufacturing, bio-fabrication

Z. Hou, Professor; Ph.D., California Institute of Technology, 1990. Vibration and control, structural dynamics, structural health monitoring, smart materials and adaptive structures, stochastic mechanics, solid mechanics, finite elements, earthquake engineering

N. Karanjgaokar, Assistant Professor; Ph.D., University of Illinois at Urbana-Champaign, 2013. Experimental mechanics at micro/nano-scale, temperature and rate dependent mechanics of nanostructured materials, dynamic response and flow of granular media, mechanics and damage of inhomogeneous materials, optical measurement techniques

D. A. Lados, Milton Prince Higgins II Distinguished Associate Professor of Mechanical Engineering; Director, Integrative Materials Design Center (iMdc); Ph.D., Worcester Polytechnic Institute, 2004. Fatigue, fatigue crack growth, thermo-mechanical fatigue, creep, and fracture of metallic materials – life predictions, computational modeling and ICME, materials/process design and optimization for aerospace, automotive, marine, and military applications; advanced material characterization; additive manufacturing, metal matrix nano–composites, friction stir welding, cold spray technology, powder metallurgy; residual stress; plasticity; fracture mechanics

Z. Li, Assistant Professor; Ph.D., University of California at Santa Cruz, 2014. Robotic manipulator motion control; design and optimization of robotic systems; medical robots; teleoperation, haptics, and human-robot interaction.

J. Liang, Associate Professor, Ph.D. (Electrical Engineering), Brown University 2004. Nonfabrication through non-lithographic approaches; heteroepitaxial growth of high quality quantum dots and semiconductor thin films on nano-patterned substrates for electronic, optic, and biomedical applications

Y. Liu, Assistant Professor; Ph.D., University of Maryland, 2011. Fiber optical tweezers, silicon nanophotonics and nanomechanics, optofluidics, fiber optic sensors, cell mechanics, biomimetics

M. M. Makhlouf, Professor; Ph.D., Worcester Polytechnic Institute, 1990. Solidification of metals, heat, mass and momentum transfer in engineering materials problems, processing of ceramics materials

B. Mishra, Kenneth G. Merriam Professor; Assoc. Director, Metal Processing Institute, Ph.D., University of Minnesota, 1986. Physico-chemical processing of materials, corrosion science and engineering, resource recovery & recycling, critical materials extraction, iron and steelmaking, alloy development, thin film coatings and surface engineering

D. J. Olinger, Associate Professor; Ph.D., Yale University, 1990. Fluid mechanics, aero- and hydrodynamics, fluid structure interaction, fluid flow control, renewable energy

C. D. Onal, Assistant Professor; Ph.D., Carnegie Mellon University, 2009. Unconventional approaches to robotics, fluidic and shape memory actuation of soft materials or mechanisms, printable robotics

B. Panchapakesan, Associate Professor, Ph.D., University of Maryland, 2001. Scalable nanomanufacturing, energy efficient photomechanical actuators, micro/nano-opto-mechanical systems, nanotube liquid crystals, 2-D nano-materials, large stimuli responsive transformation of ternary composites and utilizing micro and nanotechnology approaches to detect circulating tumor cells

P. M. Rao, Assistant Professor, Ph.D., Stanford University, 2013. Solar energy materials, photovoltaic and photoelectrochemical materials, scalable synthesis of nanostructured thin film materials

M. W. Richman, Associate Professor, Graduate Committee Chair; Ph.D., Cornell University, 1984. Mechanics of granular flows, powder compaction, powder metallurgy

B. J. Savilonis, Professor; Ph.D., State University of New York at Buffalo, 1976. Thermofluids, biofluids and biomechanics, energy, fire modeling

S. S. Shivkumar, Professor; Ph.D., Stevens Institute of Technology 1987. Plastics, materials science and engineering, biomaterials, food engineering

R. D. Sisson, Jr., George F. Fuller Professor; Director, Manufacturing and Materials Engineering, Ph.D., Purdue University, 1975. Materials process modeling and control, manufacturing engineering, corrosion, environmental effects on metals and ceramics

W. Soboyejo, Professor, Dean of Engineering; Ph.D., Cambridge University, 1988. Biomaterials, use of nanoparticles for detection and treatment of disease, mechanical properties of materials, use of materials science to promote global development.

J. M. Sullivan, Jr., Professor, Associate Department Head; D.E., Dartmouth College, 1986. Development of graphics tools and mesh generation, numerical analysis of partial differential equations, medical image visualization and analysis software development

Y. Wang, Associate Professor; Ph.D., University of Windsor, 2008. Fuel cell and battery technology, ultrahigh energy density electrodes for lithium ion batteries

Emeritus

R. Biederman, Professor Emeritus
J. M. Boyd, Professor Emeritus
A. H. Hoffman, Professor Emeritus
J. A. Mayer, Jr., Professor Emeritus
R. L. Norton, Professor Emeritus
R. J. Pryputniewicz, Professor Emeritus

Areas of Study

The graduate curriculum is divided into five distinct areas of study:

- Fluids Engineering
- Dynamics and Controls
- Structures and Materials
- Design and Manufacturing
- Biomechanical Engineering

These areas support the research interests of the mechanical engineering faculty, which are described under Areas of Research. Graduate courses introduce students to fundamentals of mechanical engineering while simultaneously providing the background necessary to become involved with the ongoing research of the mechanical engineering faculty.

Students also receive credit for special topics under ME 593 and ME 693, and independent study under ISP. Faculty members often experiment with new courses under the special topics designation, although no course may be offered more than twice in this manner. Except for certain 4000-level courses permitted in the B.S./ Master's program, no undergraduate courses may be counted toward graduate credit.

Programs of Study

The Mechanical Engineering Program offers the following graduate degree options:

- Master of Science (M.S.)
- Combined B.S./M.S.
- Doctor of Philosophy (Ph.D.)
- Graduate Certificate Program: Mechanical Engineering for Technical Leaders

Admission Requirements

For the M.S. program, applicants should have a B.S. in mechanical engineering or in a related field (i.e., other engineering disciplines, physics, mathematics, etc.).

The standards are the same for admission into the thesis and non-thesis options of the M.S. program. At the time of application to the master's program, the student must specify his/her option (thesis or non-thesis) of choice.

For the Ph.D., a bachelor's or master's degree in mechanical engineering or in a related field (i.e., other engineering disciplines, physics, mathematics, etc.) is required.

The Mechanical Engineering Department reserves its financial aid for graduate students in the Ph.D. program or in the thesis option of the M.S. program.

Degree Requirements

M.S. Program

When applying to the master of science program, students must specify their intention to pursue either the thesis or non-thesis M.S. option. Both the thesis and non-thesis options require the completion of 30 graduate credit hours. Students in the thesis option must complete 12 credits of thesis research (ME 599), whereas students in the non-thesis option may complete up to 9 credits of directed research (ME 598). The result of the research credits (ME 599) in the thesis option must be a completed master's thesis. The number of directed research credits (ME 598) completed in the non-thesis option can range from 0 to 9.

In the thesis option, the distribution of credits is as follows:

- 9 graduate credits in mechanical engineering
- 12 credits of thesis research (ME 599)
- ME 5000 (2 credits) or 3 credits of graduate-level mathematics
- 6 graduate credits of electives within or outside of mechanical engineering

In the non-thesis option, the distribution of credits is as follows:

- 18 graduate credits in mechanical engineering (includes a maximum of 9 credits of directed research—ME 598)
- 3 graduate credits in mathematics
- 9 graduate credits of electives within or outside of mechanical engineering

In either option, all full-time students are required to register for the graduate seminar (ME591) every semester.

Academic Advising

Upon admission to the M.S. program, each student is assigned or may select a temporary advisor to arrange an academic plan covering the first 9 credits of study. This plan must be made before the first registration. Prior to registering for additional credits, the student must specify an academic advisor with whom the remaining course of study is arranged. The plan must be approved by the mechanical engineering graduate committee.

For students in the thesis option, the academic advisor is the thesis advisor. Prior to completing more than 18 credits, every student in the thesis option must form a thesis committee that consists of the thesis advisor and at least two other mechanical engineering faculty members from WPI with knowledge of the thesis topic.

The schedule of academic advising is as follows:

- Temporary advisor—meets with student prior to first registration to plan the first 9 credits of study.
- Academic advisor—selected by student prior to registering for more than 9 credits. For thesis option students, the academic advisor is the thesis advisor.
- Plan of Study—arranged with academic advisor prior to registering for more than 9 credits.
- Thesis committee (thesis option only) —formed prior to registering for more than 18 credits. Consists of the thesis advisor and at least two other mechanical engineering faculty members from WPI.

This schedule ensures that students are well advised throughout the program, and that students in the thesis option are actively engaged in their research at the early stages of their programs.

Thesis Defense

Each student in the thesis option must defend his/her research during an oral defense, which is administered by an examining committee that consists of the thesis committee and a representative of the mechanical engineering graduate committee who is not on the thesis committee. The defense is open to public participation and consists of a 30-minute presentation by the student followed by a 30-minute open discussion. At least one week prior to the defense each member of the examining committee must receive a copy of the thesis. One additional copy must be made available for members of the WPI community wishing to read the thesis prior to the defense. Public notification of the defense must be given by the mechanical engineering graduate secretary. The examining committee will determine the acceptability of the student's thesis and oral performance. The thesis advisor will determine the student's grade.

Changing M.S. Options

Students in the non-thesis M.S. option may switch into the thesis option at any time by notifying the mechanical engineering graduate committee of the change, provided that they have identified a thesis advisor, formed a thesis committee, and have worked out a Plan of Study with their thesis advisor. Subject to the thesis advisor's approval, directed research credits (ME 598) earned in the non-thesis option may be transferred to thesis research credits (ME 599) in the thesis option.

Any student in the thesis option M.S. program may request a switch into the non-thesis option by submitting the request in writing to the mechanical engineering graduate committee. Before acting on such a request, the graduate committee will require and seriously consider written input from the student's thesis advisor. Departmental financial aid given to the thesis-option students who are permitted to switch to the non-thesis option will automatically be withdrawn. Subject to the approval of the mechanical engineering graduate committee, a maximum of 9 credits of thesis research (ME 599) earned by a student in the thesis option may be transferred to directed research credit (ME 598) in the non-thesis option.

The Combined Bachelor's/ Master's Program

The Mechanical Engineering Department offers a B.S./Master's program for currently enrolled WPI undergraduates. Students in the B.S./Master's program may choose either the thesis or non-thesis M.S. option. The department's rules for these programs vary somewhat from the Institute's rules. For students in the B.S./Master's program, a minimum of six credits and a maximum of twelve credits may be counted toward both the undergraduate and graduate degrees. At least six must be from graduate course credits (including graduate-level independent study and special topics courses), and none may be from courses lower than the 4000-level. No extra work is required in the 4000-level courses. A grade of B or better is required for any course to be counted toward both degrees.

The application for the B.S./Master's program must include a list of courses that the applicant proposes to count toward both his/her undergraduate and graduate degrees. In most cases, the list consists of courses that the applicant will take in the senior year.

Applications will not be considered if they are submitted prior to the second half of the applicant's junior year. Ideally, applications (including recommendations) should be completed by the early part of the last term (usually D-term) of the junior year.

Acceptance into the B.S./Master's program means that the candidate is qualified for graduate school, and signifies approval of the courses listed for credit toward both the undergraduate and graduate degrees. However, admission is contingent upon the completion of six graduate credits (from the submitted list) with grades of B or better in each. If grades of C or lower are obtained in any other listed courses, then they are not counted toward the graduate degree, but the applicant is still admitted to the program.

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Students in the B.S./Master's program who choose the thesis M.S. option are encouraged to pick a thesis area of research that is closely related to the subject of their major qualifying project. Those students in the B.S./Master's program who complete their B.S. degrees in May and choose the thesis option are encouraged to begin their thesis research during the summer immediately following graduation.

A detailed written description of the B.S./Master's program in mechanical engineering can be obtained from the mechanical engineering graduate secretary.

Ph.D. Program

The course of study leading to the Ph.D. degree in mechanical engineering requires the completion of 90 credits beyond the bachelor's degree, or 60 credits beyond the master's degree. For students proceeding directly from B.S. degree to Ph.D. degree, the 90 credits should be distributed as follows:

Coursework:	
Courses in M.E. (incl. Special Topics and ISP)	15 credits
Courses in or outside of M.E.	15 credits
Dissertation Research (ME 699)	30 credits
Other:	
Additional coursework Additional Dissertation Research (ME 699) Supplemental Research (ME 598, ME 698)	30 credits
TOTAL	90 credits

For students proceeding from master's to Ph.D. degree, the 60 credits should be distributed as follows:

Coursework:	
(incl. Special Topics and ISP)	12 credits
Dissertation Research (ME 699)	30 credits
Other:	
Additional coursework Additional Dissertation Research (ME 699) Supplemental Research (ME 598, ME 698)	18 credits
TOTAL	60 credits

In either case, the result of the dissertation research must be a completed doctoral dissertation. Only after admission to candidacy may a student receive credit toward dissertation research under ME 699. Prior to admission to candidacy, a student may receive up to 18 credits of predissertation research under ME 698. All full-time students are required to register for the graduate seminar (ME 591)every semester.

Academic Advising

Upon admission to the Doctoral Program, each student is assigned or may select a temporary advisor to arrange an academic plan covering the first 9 credits of study. This plan should be arranged before the first day of registration.

Prior to registering for any additional credits, the student must identify a permanent dissertation advisor who assumes the role of academic advisor and with whom a suitable dissertation topic and the remaining Plan of Study are arranged. Prior to completing 18 credits, the student must form a dissertation committee that consists of the dissertation advisor, at least two other mechanical engineering faculty members, and at least one member from outside the department. These committee members should be selected because of their abilities to assist in the student's dissertation research.

The schedule of advising is as follows:

- Temporary advisor—meets with student prior to first registration to plan first 9 credits of study.
- Dissertation advisor—selected by student prior to registering for more than 9 credits.
- Program of study—arranged with Dissertation advisor prior to registering for more than 9 credits.
- Dissertation committee—formed by student prior to registering for more than 18 credits. Consists of dissertation advisor, at least two M.E. faculty, and at least one outside member.

This schedule ensures that students are well advised and actively engaged in their research at the early stages of their programs.

Admission to Candidacy

Admission to candidacy will be granted when the student has satisfactorily passed a written exam intended to measure fundamental ability in three of the following five curriculum areas: fluids engineering, dynamics and controls, structures and materials, design and manufacturing, and biomechanical engineering. The three areas are selected by the student. The exam is given in January. For students who enter the program with a bachelor's degree, the exam must be taken after three semesters if they began their studies in the fall, and after two semesters if they began in the spring. For students who enter the program with a master's degree, the exam must be taken after one semester if they began in the fall, and after two semesters if they began in the spring. Students in the M.S. program who plan to apply for fall admission to the Ph.D. program are strongly advised to take the candidacy exam in January before that fall. The details of the examination procedure can be obtained from the mechanical engineering graduate committee.

Dissertation Proposal

Each student must prepare a brief written proposal and make an oral presentation that demonstrates a sound understanding of the dissertation topic, the relevant literature, the techniques to be employed, the issues to be addressed, and the work done on the topic by the student to date. An important part of the written and oral proposal should be a description of the potential applications and societal impact of the research. The proposal must be made within 18 months of admission to candidacy. Both the written and oral proposals are presented to the dissertation committee and a representative from the mechanical engineering graduate committee. The prepared portion of the oral presentation should not exceed 30 minutes, and up to 90 minutes should be allowed for discussion. If the dissertation committee and the graduate committee representative have concerns about either the substance of the proposal or the student's understanding of the topic, then the student will have one month to prepare a second presentation that focuses on the areas of concern. This presentation will last 15 minutes with an additional 45 minutes allowed for discussion. Students can continue their research only if the proposal is approved.

Dissertation Defense

Each doctoral candidate is required to defend the originality, independence and quality of research during an oral dissertation defense that is administered by an examining committee that consists of the dissertation committee and a representative of the mechanical engineering graduate committee who is not on the dissertation committee. In addition to providing a summary of the relevant literature and a description of the techniques employed, technical issues addressed, and results obtained, both the dissertation and the oral defense should include a description of the potential applications and societal impact of the research. The defense is open to public participation and consists of a 45-minute presentation followed by a 45-minute open discussion. At least one week prior to the defense, each member of the examining committee must receive a copy of the dissertation. At the same time, an additional copy must be made available for members of the WPI community wishing to read the dissertation prior to the defense, and public notification of the defense must be given by the mechanical engineering graduate secretary. The examining committee will determine the acceptability of the student's dissertation and oral performance. The dissertation advisor will determine the student's grade.

Graduate Certificate Program: Mechanical Engineering for Technical Leaders (METL)

Companies recognize that employees who pursue graduate education oftentimes become the future technical leaders within their organization. As leaders, it is important that they possess not only the engineering skills to understand technical problems that require novel and innovative solutions, but also the business and managerial skills to harness the resources (human and capital) to implement these solutions. This certificate combines graduate mechanical engineering coursework to enhance their technical expertise along with leadership and management coursework to empower them to lead technical teams, make sound business decisions and bring their projects to successful conclusion.

Requirements:

9 credits in graduate level Mechanical Engineering courses*

9 credits in graduate level Business courses**

* Note: Students may petition the Mechanical Engineering Graduate Committee to count up to 4 credits in AE and/or MTE graduate courses. Petitions must be approved before students register for these AE and or MTE credits.

** Note: Students may use CE 580 (Advanced Project Management) toward this requirement.

Admission to the Certificate Program:
Students wishing to enroll in the METL Certificate program must submit a full M.S. graduate application.

Successful Completion of the METL Certificate Program:
Successful completion of the METL certificate program requires:

- completion of the 18 credits distributed as described above; and
- an overall GPA of at least 3.0.

Subsequent Admission into the M.S. program in Mechanical Engineering:
Students wishing to continue their studies in the M.S. program in Mechanical Engineering will be admitted upon request provided that they have:

- completed the METL certificate program; and
- earned a GPA of at least 3.0 within the 9 credits of M.E. courses (including any AE and MTE credits permitted by petition).

For students who continue on to the M.S. program in Mechanical Engineering, any AE or MTE credits that have been used to satisfy the METL certificate requirements will be counted as M.E. credits toward the M.S. degree.

Areas of Research

The faculty of the Mechanical Engineering Department currently pursue research under the following areas:

- Dynamics, Controls and Robotics
- Energy Science and Engineering
- Materials and Manufacturing
- Mechanics and Design
- Nano and Micro Engineering

Please consult the Mechanical Engineering Department website for a current list of the faculty pursuing research under each of these areas.

Mechanical Engineering Laboratories and Centers

The Mechanical Engineering Program provides a multidisciplinary research and education environment. The facilities are housed in Higgins Laboratories and Washburn Shops. For the laboratories and centers of the other programs within the Mechanical Engineering Department (Aerospace Engineering, Manufacturing Engineering, Materials Process Engineering, and Materials Science and Engineering), please see their corresponding sections in this catalog.

Teaching and Project Laboratories

Design Studio and Computer Classroom

The Higgins Design Studio (HL 234) and the Computer Classroom (HL 230) are both part of the Keck Design Center, and are managed by WPI's Information Technology Services Division. The labs are used for lectures and laboratories in a variety of mechanical design and manufacturing courses, and are also available to students for general-purpose computational work on projects and coursework. The 1600 sq. ft. Higgins Design Studio contains twenty one (21) high-end workstations running software for mechanical design including parametric solid modeling (PTC/Creo, Solidworks, NX, Ideas), structural, thermal, fluid and dynamic analysis (ANSYS, Abaqus, Nastran, Patran, Fluent, Comsol) and general purpose applications (Tecplot, sigmaplot, Mathematica, MatLab, Maple). Auxiliary equipment includes two laser printers and 2 E-size color printer/plotter. The 1575 sq. ft. Computer Classroom (HL 230) contains more than forty (40) workstations, A/V equipment including dual high-resolution projection systems, and a high-speed laser printer. Locally installed software includes Solidworks, AutoCAD, Matlab, Maple, Mathcad, TK Solver, Thermal Analysis software and VisualStudio. Net. The workstations in the Design

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Studio and Computer Classroom have access to all software available on the WPI campus network, and allow for design collaboration and exchange of design models to manufacturing facilities. Courses served: ES 1020, ES 1310, ME 3310, ME 3311, ME 3320, ME 4320 and many out-of- department courses.

Experimentation Laboratory

The Experimentation Laboratory (HL 031) provides the Mechanical Engineering Department with a modern laboratory for the state-of-art Engineering Experimentation ME 3901 course, required for ME students to satisfy their experimentation requirement. The course provides students with valuable hands-on knowledge and directly addresses all ABET experimentation and related requirements. The 1300 sq. ft. laboratory houses 15 workstations containing Labview-based data acquisition hardware and software. Each workstation is configured for two students working in pairs. A host of standard sensors and transducers (thermocouples, thermistors, RTDs, strain gages, pressure transducers, accelerometers, etc.) complement each workstation bench. The laboratory also contains standard test equipment (DVM, soldering equipment, hand tools, calipers, and micrometers) as well as hardware apparatus such as pressure tanks, orifices, heat exchangers, pressurized air, power, and internet, etc. This laboratory is also used for ES 3011 Engineering Controls I, ME 4322 Modeling and Analysis of Mechatronics, a graduate course on Dynamic Signal Analysis, and MQP projects related to engineering experimentation.

MQP Laboratory

The MQP Laboratory (HL 045) is a 450 sq. ft. space for students to assemble and work on their MQP projects,. The laboratory lies between the Engineering Experimentation Laboratory, giving access to state-of-art electronic sensors and measurement equipment, and the Higgins Machine Shop, providing lathes, drill presses, milling machines and CNC equipment. The MQP laboratory is equipped with air, water, drains, and hand-tools for fabrication work. Individualized storage exists for capstone design works in progress.

Project Laboratories

The other project laboratory spaces in Higgins Laboratories include HL 005, 006, 017, and 019. HL 005 (1600 sq. ft.) is used primarily to conduct of capstone design projects requiring a large work and assembly area. It also provides space to one of WPI's US First Robotics teams and supports the Robotics Resource Center (HL 009), as well as being the home of WPI's CollabLab, which is a student organization that promotes "maker" culture and collaboration at WPI. The SAE Project Lab (HL 006, 300 sq. ft.) houses the SAE Formula Race Car and other SAE projects. HL 017 and 019 (each approximately 100 sq. ft.) provide further space and resources for conducting course projects and MQP projects.

Manufacturing Facilities

3D Print Laboratory

Rapid Prototyping (RP) technologies, including 3D printing, use a computer-driven, additive process to print solid three-dimensional models one layer at a time almost directly from a computer-aided design (CAD) program. The 3D Print Laboratory (HL 232) houses two executive level RP machines managed by Academic & Research Computing (ARC) Center staff available for students, faculty, and staff across campus. The Dimension SST 1200es prints exclusively with ABS plastic, and the Objet 260 Connex is capable of using a variety of resins that can produce up to 14 different material properties within one part, with over 60 material options available. Submissions to the machines are accepted for any on campus projects (MQP, IQP, course project, graduate research, etc.) that have been approved by an advisor or faculty member, for the production of parts that cannot be easily purchased or created using other on campus resources. Instructions for access can be found at https://www.wpi.edu/offices/it/facilities-resources.html, and the staff can be contacted at rapidprototyping@wpi.edu

CNC Teaching Laboratory

The CNC teaching laboratory is located in the Washburn Shops Room 107 and covers 3,140 sq. ft. The CNC machine tools housed within this lab are used for a wide range of student projects including MQPs, and also in ME 1800, ME 3820, and other courses. The laboratory is equipped with one Universal Laser Systems VLS60 Laser Cutter, one Makerbot Replicator 2X, 3 Haas MiniMills and 2 Haas SL10s, 3 band saws, two drill presses, a sheet metal shear and bending break as well as assorted hand tools. Attached to each of the MiniMills and SL10s are computer workstations equipped design and programming software. In addition to the computers located at each of the CNC machine tools, the facility has two computer classrooms, one in Washburn 107 and the other in Washburn 105, which can be configured to contain between 8 and 12 computer workstations. These workstations have access to the design software packages supported on campus as well as our training materials and several Computer Aided Manufacturing (CAM) software packages including Esprit, MasterCam, and SurfCam. The facilities are run by an operations manager and lab machinists who are assisted by undergraduate peer learning assistants (PLAs).

Higgins Machine Shop

The 600 sq. ft. machine shop in Higgins Labs is located in HL 004, and contains 2 CNC Machine tools (a Haas Tool Room Mill and a Haas Tool Room Lathe), as well as a surface grinder, 2 DoAll Mills and a DoAll engine lathe as well as a drill press, 2 band saws and assorted hand tools. A machinist manages and supports the machine shop and project activities with the assistance of undergraduate PLAs.

MEMS Fabrication Laboratory

The MEMS Fabrication Laboratory (HL 106) is a Class 100 cleanroom facility with approximately 500 square feet of floor space, including the gowning area. It is equipped with instrumentation to support photolithography, thermal deposition and oxidation, wet chemistry, metrology, and wafer bonding. Metrology capabilities for the devices that are fabricated, such as profilometry, SEM, AFM, and XRD are available through other ME Department laboratories, including the Materials Characterization Laboratory (see Materials Science and Engineering section of this catalog).

Research Laboratories

Automation and Interventional Medicine Laboratory

The Automation and Interventional Medicine Laboratory (AIM Lab) is located at 85 Prescott Street (Gateway Park). The primary focus of projects in the AIM Lab is medical robotics including: robotic surgery, image-guided surgery, MRI-compatible mechatronics, rehabilitation robotics, socially assistive robotics, and biofabrication. The lab contains 10 student workstations, equipment for mechanical and electrical design, construction, configuration, and testing of robots, control systems, and automated test fixtures, including state-of-the-art electronics testing and micro-electronics assembly equipment and supplies. An NDI Polaris optical tracker is available for motion capture. The lab houses MRI robot controllers developed in the AIM lab and custom control electronics for high precision control of piezoelectric motor drive waveforms and corresponding robotic system testbeds. A daVinci Research Kit (dVRK) surgical robot is also available in the lab which includes the Intuitive Surgical robot with custom open control systems. Additional access to a 3T Philips MRI scanner and affiliated personnel is available through collaboration with the nearby UMass Medical School. Collaboration with the Brigham and Women's Hospital provides a second clinical site. BWH has specially configured scanners for real-time image acquisition and scanner control readily implemented with the robot. The Advanced Multimodality Image Guided Operating (AMIGO) suite provides an ideal clinical validation environment. The research in the AIM Lab is directed by Prof. G. Fischer. Further information can be found at http://aimlab.wpi.edu/.

Multi-Scale Heat Transfer Laboratory

The Multi-Scale Heat Transfer (MHT) Laboratory is located in HL 248, and investigates the enhancement of heat transfer and mass transport in nano-, micro-, and macro-scales, with and without working fluid phase change (liquid/vapor), in the presence and absence of gravity utilizing various mechanisms of electrohydrodynamics (EHD). The MHT Laboratory also studies the augmentation of heat transfer with micro-scale phase change materials under various fluid flow configurations. MHT Laboratory features the following two-phase flow experimental apparatuses: EHD pump in micro scale for water droplet activation; multi-functional in-tube (internal forced convection) condensation and boiling in horizontal configuration using EHD polarization force; external condensation in horizontal configuration using EHD induction pumping; external condensation in vertical configuration using EHD polarization force; in-channel (internal forced convection) condensation in horizontal configuration using EHD induction pumping; two-phase loop with EHD induction pumping; and pool boiling for low and high pressure refrigerants using EHD polarization force. Supporting equipment include a large scale two-phase system (heat pipe loop), a unique high voltage, three-phase power supply, several high voltage (0-50kV) dc power supplies, a high-speed video system, micro-fiber optic temperature measurement device, thermistors, heat flux sensors, pressure transducers, flow meters, vacuum pumps, recirculating chillers, oscilloscope, multi-meters, and desktop computers. The research in the MHT Lab is directed by Prof. Prof. J. Yagoobi. Further information can be found at http://mht.wpi.edu/.

NanoEnergy Laboratory

The NanoEnergy Lab is located in HL 026, and targets the synthesis and study of nanomaterials for energy conversion applications, particularly for converting solar energy to electrical or chemical energy (photovoltaic and photoelectrochemical energy conversion). The goal is to use nanostructuring and scalable, economical synthesis methods to dramatically improve the energy conversion efficiency of earth-abundant, low-cost materials. Materials synthesis equipment in the NanoEnergy Lab includes vapor deposition (flat-flame burner and multi-zone tube furnace), hydrothermal synthesis reactors, solution deposition (fume hood, spincoater), and various furnaces for annealing materials. Light sources, integrating spheres, spectrometers, a potentiostat, electrochemical cells and chemical sensors are available for the characterization of optical, electronic, photovoltaic and photoelectrochemical properties and behavior of materials. The research in the NanoEnergy Lab is directed by Prof. P. Rao. Further information can be found at http://nanoenergy.wpi.edu/.

Optomechanics Laboratory

The WPI Optomechanics Lab is located in HL 029, 037 and 039. The overarching goal is to develop tools based on coupling between optics and mechanics at the micro- and nanoscale, and applying these tools to tackle challenging problems at the intersection of various disciplines. The main research carried out includes fiber optical tweezers, silicon nanomechanics, silicon nanophotonics, optofluidics, and fiber optic sensors. The research in the Optomechanics Lab can find applications in cell mechanics, on-chip disease diagnosis, precision displacement/force measurements, and biomedical sensing. The lab has various facilities for optical and mechanical research at the micro/nanoscale, such as a tunable diode laser, pigtailed laser diodes, automatic fiber fusion splicers, fiber end polisher, and a large variety of photodetectors and power meters. There are various microscopes available for imaging and measurements, including one research-grade inverted fluorescence microscope for biological research and a long-working-distance microscope for nanophotonic and microfluidic research. The lab is specialized in home-made fiber optical tweezer systems, which enable non-contact nanoparticle manipulation and picoNewton force measurements. Piezo stages and a 6-GHz electronic spectrum analyzer enable nanometer displacement control and GHz-range dynamic signal measurements. The research in the Optomechanics Laboratory is directed by Prof. Y. Liu. Further information can be found at http://optomech.wpi.edu/.

Small Systems Laboratory

The Small Systems Laboratory (SSL) is located in HL 124, and is dedicated to the development of multi-functional materials, devices and systems at the macro-, micro-, meso- and nanoscales. Our work spans multiple areas bridging multiple disciplines and multiple length scales. Facilities at SSL include fabrication and characterization units for advanced materials, device processing and testing

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and biomaterials characterization. Specific ongoing research projects are in the area of novel nanocomposites, energy efficient materials and devices, stimuli responsive materials, photoconductive devices and biomedical nanotechnology. Research in the SSL is directed by Prof. B. Panchapakesan. Further information can be found at http://www.baloolab.org/.

Soft Robotics Laboratory

The Soft Robotics Laboratory is located in HL 127, and supports personnel and equipment required for the design, fabrication, and low-level control of next-generation soft, flexible, and semi-rigid robotic systems. Lab facilities include four Windows/Linux workstations with state-of-the-art design, modeling, and analysis software. Equipment in the Soft Robotics lab includes devices for design, fabrication, experimentation, and analysis, including an Epilog Zing 24 CO2 laser cutter, a vertical drill-press, various semi-rigidware packages for mechanical and electronic design, a full custom-made flexible circuit fabrication and assembly equipment suite, a large-workspace optical microscope, an elastomeric fabrication workbench, and various data acquisition and analysis systems. The lab currently supports research activities in elastomeric robotic systems, printed circuit and sensor manufacturing, origami-inspired foldable systems, assistive soft robotic monitoring, bio-inspired stereo vision, and prosthetic robotics. Research in the Soft Robotics Laboratory is directed by Prof. C. Onal. Further information can be found at http://softrobotics.wpi.edu/.

Research Centers

Center for Advanced Research in Drying

The Center for Advanced Research in Drying (CARD) is a National Science Foundation (NSF) Industry/University Cooperative Center (I/UCRC) devoted to research in drying of moist, porous materials such as food and other agricultural products, forestry products, chemical products, textiles, and biopharmaceuticals. CARD was founded by WPI as a lead institution, and the University of Illinois at Urbana-Champaign. Examples of the current CARD research areas include:

- Drying Processes/Systems Design and Simulation
- Optimizing Product Quality and Energy Consumption during Drying by Solving Multi-scale Transport Models
- Nano- and Micro-Technology in Drying Applications
- Innovative Concepts in Drying of Moist Porous Materials
- Moisture Management for Food Quality, Stability and Safety
- Phase Behavior of Biopolymers and Impact on Product Quality
- Mechanical Modeling and Computer Software Tracking
- Product Microstructure and Surface Metrology Characterization
- No-Phase-Change Dehydration Schemes and Other Novel Drying Concepts
- Innovative Impinging Jets with and without Chemical Reactions for Drying, Heating, and Cooling Applications
- Energy Auditing
- Development of Unique Sensors

Research in CARD is directed by Prof. J. Yagoobi. Further information and a list of participating faculty members can be found at http://www.dryingresearch.org/.

Center for Holographic Studies and Laser micro-mechaTronics

The laboratories of the Center for Holographic Studies and Laser micro-mechaTronics (CHSLT) cover over 2,800 sq. ft and support activities ranging from fundamental studies of laser light interaction with materials to sophisticated applications in metrology. Research at the CHSLT is externally funded in areas relating to electronic packaging, high density separable electronic interconnections for high speed digital applications, radar technology, microelectronics, micromechanics, submarine technology, jet engine technology, MEMS, nanotechnology and picotechnology, to name a few. The laboratories are furnished with He-Ne lasers, Ar-ion lasers, Nd:YAG lasers, nanosecond high energy pulsed laser, and diode lasers, as well as supporting instrumentation systems. In addition, the Nano-Indentation (NIN) system is being developed for studies of mechanical properties of materials in sub-micron geometries. The CHSLT has its own computational facilities for Finite Element, Finite Difference, and Boundary Element analysis, modeling, and simulation. The metrological applications at the CHSLT concentrate on holographic interferometry, laser speckle metrology, fiber optic sensors, analytical and computational modeling of structural behavior under static as well as dynamic loading conditions, and other areas of current interest. In the area of holographic interferometry, the CHSLT maintains holographic systems for studies of static as well as dynamic problems. These systems range from conventional double-exposure holography, to real-time and time-average holography, heterodyne holography, stroboscopic heterodyne holography, pulsed laser holography, and electro-optic holography (EOH). The EOH system allows for direct electronic acquisition and processing of interferometric data in real-time and sets a new standard for quantitative holographic analysis. The CHSLT also conducts experimental and computational research in the field of nanoindentation studies in conjunction with a laboratory system which is uniquely suited to measure elastic, plastic, creep, and fracture properties of materials in submicron geometries. In addition, the CHSLT is equipped with a complete laser vibrometer system, GHz frequency range storage oscilloscopes, a spectrum analyzer, a self-contained network of personal computers, UNIX based workstations and image processors, a host of supporting instrumentation, and a library of finite element analysis and general purpose software. A well-equipped electrical engineering and instrument development laboratory, a fiber optic preparation laboratory, an optical microscopy laboratory and a multifunctional dark room are also parts of the CHSLT. The strengths of the CHSLT lie in a comprehensive utilization of laser technology, optics, computational methods, mechanical engineering, materials science and engineering, and computer data acquisition and processing. Research in CHSLT is directed by Prof. C. Furlong. Further information can be found at http://chslt.wpi.edu/.

Course Descriptions

All courses are 3 credits unless otherwise noted.

General:

ME 5000. Applied Analytical Methods in Engineering

(2 credits)

The emphasis of this course is on the modeling of physical phenomena encountered in typical engineering problems, and on interpreting solutions in terms of the governing physics. In this manner, the course will expose students to a range of techniques that are useful to practicing engineers and researchers. Physical examples will be drawn from fluid mechanics, dynamics, and structural mechanics. The course will introduce analytical techniques as they are required to study such phenomena. Depending on the examples chosen, the techniques covered may include partial differential equations, power series, Fourier series, Fourier integrals, Laplace transform methods, Green's Functions, Sturm-Liouville theory, linear algebra, and calculus of variations. (Prerequisites: differential equations at the undergraduate level.) Students cannot receive credit for this course if they have taken either the Special Topics (ME 593A) version of the same course or ME 500.

ME 5001. Applied Numerical Methods in Engineering

(2 credits)

A study of important numerical and computational methods for solving engineering science problems. The course will include methods for solving linear and nonlinear equations, interpolation strategies, evaluating integrals, and solving ordinary and partial differential equations. Finite difference methods will be developed in full for the solution of partial differential equations. The course materials emphasize the systematic generation of numerical methods for elliptic, parabolic, and hyperbolic problems, and the analysis of their stability, accuracy, and convergence properties. The student will be required to write and run computer programs. Students cannot receive credit for this course if they have taken the Special Topics (ME 593M) version of the same course or ME 515.

Fluids Engineering:

ME/AE 5101. Fluid Dynamics

(2 credits)

This course presents the following fundamental topics in fluid dynamics: concept of continuum in fluids; kinematics and deformation for Newtonian fluids; the mass conservation equation, momentum and energy equations for material volumes and control volumes; the differential form of mass conservation, momentum and energy equations. This course covers also applied topics chosen from: unidirectional steady incompressible viscous flows; unidirectional transient incompressible viscous flows; lubrication flows similarity and dimensional analysis. This is an introductory graduate-level course and may be taken independent of AE 5107/ME 5107.

ME/AE 5104. Turbomachinery

(2 credits)

This course is an introduction to the fluid mechanics and thermodynamics of turbomachinery for propulsion and power generation applications. Axial and centrifugal compressors will be discussed as well as axial and radial flow turbines. Analysis of the mean line flow in compressor and turbine blade rows and stages will be discussed. The blade-to-blade flow model will be presented and axisymmetric flow theory introduced. Three-dimensional flow, i.e. secondary flows, will also be discussed. Students cannot receive credit for this course if they have taken the Special Topics (ME 593H) version of the same course.

ME/AE 5105. Renewable Energy

(2 credits)

The course provides an introduction to renewable energy, outlining the challenges in meeting the energy needs of humanity and exploring possible solutions in some detail. Specific topics include: use of energy and the correlation of energy use with the prosperity of nations; historical energy usage and future energy needs; engineering economics; electricity generation from the wind; wave/ocean energy, geo-thermal and solar-thermal energy; overview of fuel cells, biofuels, nuclear energy, and solar-photovoltaic systems and their role and prospects; distribution of energy and the energy infrastructure; energy for transportation; energy storage. Pre-requisites; ES3001, ES3004 or equivalents. Students cannot receive credit for this course if they have taken the Special Topics (ME 593R) version of the same course.

ME/AE 5107. Applied Fluid Dynamics

(2 credits)

This course presents applications of incompressible and compressible fluid dynamics at an introductory graduate level. Topics are chosen from: potential flows; boundary layers; vorticity dynamics and rotating flows; aerodynamics; introduction to turbulence; micro/nano flows. This course can be taken independent of AE 5101/ME 5101.

ME/AE 5108. Introduction to Computational Fluid Dynamics

(2 credits)

The course provides the theory and practice of computational fluid dynamics at an entry graduate level. Topics covered include: classification of partial differential equations (PDEs) in fluid dynamics and characteristics; finite difference schemes on structured grids; temporal discretization schemes; consistency, stability and error analysis of finite difference schemes; explicit and implicit finite differencing schemes for 2D and 3D linear hyperbolic, parabolic, elliptic, and non-linear PDEs in fluid dynamics; direct and iterative solution methods for algebraic systems. The course requires completion of several projects using MATLAB.

ME 513. Thermodynamics

(3 credits)

Review of the zeroth, first and second laws of thermodynamics and systems control volume. Applications of the laws to heat engines and their implications regarding the properties of materials. Equations of state and introduction to chemical thermodynamics.

ME 516. Heat Transfer

(3 credits)

Review of governing differential equations and boundary conditions for heat transfer analysis. Multidimensional and unsteady conduction, including effects of variable material properties. Analytical and numerical solution methods. Forced and free convection with laminar and turbulent flow in internal and external flows. Characteristics of radiant energy spectra and radiative properties of surfaces. Radiative heat transfer in absorbing and emitting media. Systems with combined conduction, convection and radiation. Condensation, evaporation, and boiling phenomena. (Prerequisite: Background in thermodynamics, fluid dynamics, ordinary and partial differential equations, and basic undergraduate physics.)

ME/AE 6108. Intermediate Computational Fluid Dynamics

(2 credits)

The course presents computational methods for incompressible and compressible viscous flows at an intermediate level. Topics are chosen from: grid generation techniques; finite volume schemes; stability analysis; artificial viscosity; explicit and implicit schemes; flux-vector splitting; monotonic advection schemes; multigrid methods; particle-based simulation methods. (Prerequisite: fluid dynamics; an introductory course in numerical methods for partial differential equations; programming language experience) Students who have received credit for AE/ME 5103 will not receive credit for AE/ME 6108.

Dynamics and Controls:

ME 501/RBE 501. Robot Dynamics

(3 credits)

Foundations and principles of robotic manipulation. Topics include computational models of objects and motion, the mechanics of robotic manipulators, the structure of manipulator control systems, planning and programming of robot actions. The focus of this class is on the kinematics and programming of robotic mechanisms. Important topics also include the dynamics, control, sensor and effector design, and automatic planning methods for robots. The fundamental techniques apply to arms, mobile robots, active sensor platforms, and all other computer-controlled kinematic linkages. The primary applications include robotic arms and mobile robots, and lab projects would involve programming of representative robots. An end-of-term team project would allow students to program robots to participate in challenges or competitions. (Prerequisite: RBE 500 or equivalent.)

ME 5200. Mechanical Vibrations
(2 credits)

The course provides fundamentals for vibration analysis of linear discrete and continuous dynamic systems, A vibrating system is first modeled mathematically as an initial value problem (IVP) or a boundary-initial value problem (BIVP) by the Newton-D'Alembert method and/or the Lagrange energy approach and then solved for various types of system. Explicit solutions for dynamic response of a linear single-degree-of-freedom (SDOF) system, both damped and undamped, is derived for free-vibration caused by the initial conditions and forced vibration caused by different excitations. Modal analysis is presented to solve for vibration response of both multi-degree-of-freedom (MDOF) systems and continuous systems with distributed parameters. As the basis of modal analysis, the natural frequencies and vibration modes of a linear dynamic system are obtained in advance by solving an associated generalized eigenvalue problem and the orthogonal properties of the vibration modes with respect to the stiffness and mass matrices are strictly proved. Computational methods for vibration analysis are introduced. Applications include but are not limited to cushion design of falling packages, vehicles traveling on a rough surface, multi-story building subjected to seismic and wind loading, and vibration analysis of bridges subjected to traffic loading. Students cannot receive credit for this course if they have taken the Special Topics (ME 593V) version of the same course or ME522.

ME 5202. Advanced Dynamics
(2 credits)

Basic concepts and general principles of classical kinematics and dynamics of particles, systems of particles and rigid bodies are presented with application to engineering problems with complicated three-dimensional kinematics and dynamics. Derivation of the governing equations of motion using Principle of Virtual Work and Lagrange equations is described together with the direct Newton approach. Applications include: swings-effect and its use in engineering, illustrating in particular limit cycles and their stability and reversed-swings control of vibrations of pendulum; various examples of gyroscopic effects; and especially introductory rotordynamics including transverse vibrations (whirling) and potential instability of rotating shafts. Students cannot receive credit for this course if they have taken the Special Topics (ME 593D) version of the same course or ME 527.

ME 5204/RBE 510. Multi-Robot Systems
(2 credits)

This course covers the foundation and principles of multi-robot systems. The course will cover the development of the field and provide an overview on different control architectures (deliberative, reactive, behavior-based and hybrid control), control topologies, and system configurations (cellular automata, modular robotic systems, mobile sensor networks, swarms, heterogeneous systems). Topics may include, but are not limited to, multi-robot control and connectivity, path planning and localization, sensor fusion and robot informatics, task-level control, and robot software system design and implementation. These topics will be pursued through independent reading, class discussion, and a course project. The course will culminate in a group project focusing on a collaborative/cooperative multi-robot system. The project may be completed through simulation or hands-on experience with available robotic platforms. Groups will present their work and complete two professional-quality papers in IEEE format. (Prerequisites: Linear algebra, differential equations, linear systems, controls, and mature programming skills, or consent of the instructor.) Students cannot receive credit for this course if they have taken the Special Topics (ME 593S) version of the same course.

ME 5205/RBE 580. Biomedical Robotics
(2 credits)

This course will provide an overview of a multitude of biomedical applications of robotics. Applications covered include: image-guided surgery, percutaneous therapy, localization, robot-assisted surgery, simulation and augmented reality, laboratory and operating room automation, robotic rehabilitation, and socially assistive robots. Specific subject matter includes: medical imaging, coordinate systems and representations in 3D space, robot kinematics and control, validation, haptics, teleoperation, registration, calibration, image processing, tracking, and human-robot interaction.Topics will be discussed in lecture format followed by interactive discussionof related literature. The course will culminate in a team project covering one or more of the primary course focus areas. Recommended background: Linear algebra, ME/RBE 501 or equivalent Students cannot receive credit for this course if they have taken the Special Topics (ME 593U) version of the same course.

ME/AE 5220. Control of Linear Dynamical Systems
(2 credits)

This course covers analysis and synthesis of control laws for linear dynamical systems. Fundamental concepts including canonical representations, the state transition matrix, and the properties of controllability and observability will be discussed. The existence and synthesis of stabilizing feedback control laws using pole placement and linear quadratic optimal control will be discussed. The design of Luenberger observers and Kalman filters will be introduced. Examples pertaining to aerospace engineering, such as stability analysis and augmentation of longitudinal and lateral aircraft dynamics, will be considered. Assignments and term project (if any) will focus on the design, analysis, and implementation of linear control for current engineering problems. The use of Matlab®/Simulink® for analysis and design will be emphasized. (Recommended background: Familiarity with ordinary differential equations, introductory control theory, fundamentals of linear algebra, and the analysis of signals and systems is recommended. Familiarity with Matlab® is strongly recommended.) Students cannot receive credit for this course if they have taken the Special Topics (ME 593N) version of the same course or ME 523.

ME/AE 5221. Control of Nonlinear Dynamical Systems
(2 credits)

Overview of stability concepts and examination of various methods for assessing stability such as linearization and Lyapunov methods. Introduction to various design methods based on linearization, sliding modes, adaptive control, and feedback linearization. Demonstration and performance analysis on engineering systems such as flexible robotic manipulators, mobile robots, spacecraft attitude control and aircraft control systems. Control synthesis and analysis is performed using Matlab®/Simulink®. (Prerequisites: Familiarity with ordinary differential equations, introductory control theory at the undergraduate level, fundamentals of linear algebra. Familiarity with Matlab® is strongly recommended.) Students cannot receive credit for this course if they have taken the Special Topics (ME 593N) version of the same course or ME 623.

ME 5225. Fiber Optical Sensors
(2 Credits)

This course is designed to introduce students to the field of fiber optics, with an emphasis on design and working principles of fiber optical sensors for mechanical, biological, and chemical measurements. It covers basic knowledge and working principles of optical fibers and fiber optical components, as well as practical design guidelines and applications of fiber optical sensing systems. The first half of the course will introduce different aspects of fiber optics, including working principles of optical fibers, single-mode and multimode fibers, properties of optical fibers, passive fiber optical devices, light sources, and optical detectors. The second half of the course will focus on various fiber optical sensors and sensing systems, including working principles of fiber optical sensors, intensity-based and interferometer-based fiber optical sensors, fiber Bragg gratings, and low-coherence fiber optical interferometers. Specifically, design and implementation of fiber optical sensors and sensing systems for strain and pressure measurements will be discussed in detail. Measurement characteristics and signal processing of fiber optical sensing systems for different applications will be introduced.

Recommended Background: ES 2502, PH 1140. ME 4506 is preferred but not required.

ME 6201. Advanced Topics in Vibration
(2 credits)

The course presents advanced topics in vibrations of machines and structures: dynamic stability analysis for linear nonconservative systems with applications to aeroelasticity and rotordynamics such as whirling of shafts with internal energy dissipation; introduction into theory of nonlinear and parametric vibrations in machines and structures; probabilistic approach in dynamics – analysis of random vibrations with applications to reliability evaluation in earthquake engineering, offshore engineering, etc. Use of random vibration analyses is illustrated for on-line condition monitoring for machines and structures (mechanical signature analysis), such as detecting instability and evaluating stability margin for a nonconservative system from its on-line measured signal. Introduction into general vibration theory makes the course self-contained (background in ME 522 preferable but not necessary). Students cannot receive credit for this course if they have taken the Special Topics (ME 593B) version of the same course.

ME 621. Dynamics and Signal Analysis
(3 credits)

A laboratory-based course which applies Fourier and cepstral signal analysis techniques to mechanical engineering problems. The theory and application of the Fourier series, Fast Fourier Transform (FFT) and the cepstrum to the analysis of mechanical and acoustical systems is presented. Digital sampling theory, windowing, aliasing, filtering, noise averaging and deconvolution are discussed. Limitations of and errors in implementation of these techniques are demonstrated. Students will perform weekly experiments in the Structural Dynamics and Vibration Laboratory, which reinforce the theories presented in lectures. Application will include structures, acoustics, rotating machinery and cams.

Structures and Materials:

ME/CE 5303. Applied Finite Element Methods in Engineering
(2 credits)

This course is devoted to the numerical solution of partial differential equations encountered in engineering sciences. Finite element methods are introduced and developed in a logical progression of complexity. Topics covered include matrix structural analysis variation form of differential equations, Ritz and weighted residual approximations, and development of the discretized domain solution. Techniques are developed in detail for the one- and two-dimensional equilibrium and transient problems. These numerical strategies are used to solve actual problems in heat flow, diffusion, wave propagation, vibrations, fluid mechanics, hydrology and solid mechanics. Weekly computer exercises are required to illustrate the concepts discussed in class. Students cannot receive credit for this course if they have taken the Special Topics (ME 593E) version of the same course or ME 533 or CE 524.

ME 5304. Laser Metrology and Nondestructive Testing
(2 credits)

Demands for increased performance and efficiency of components in the nano/micro-, meso-, and macro-scales, impose challenges to their engineering design, study, and optimization. These challenges are compounded by multidisciplinary applications to be developed inexpensively in short time while satisfying stringent design objectives. As a consequence, effective quantitative engineering methodologies, such as optical techniques, are frequently used in the study and optimization of advanced components and systems. In this course, modern laser metrology techniques are discussed and their practical applications to solve problems, with emphasis on nondestructive testing (NDT), are illustrated with laboratory demonstrations. Topics covered include wave and Fourier optics, classic and holographic interferometry, speckle techniques, solid-state lasers, fiber optics, CCD cameras, computer vision, camera calibration methods, and image processing and data reduction algorithms as required in quantitative fringe analysis. Detail examples of nondestructive testing and coherent optical metrology in solid mechanics, vibrations, heat transfer, electromagnetics, and reverse engineering are given. Students are required to work on projects depending on their background and interests. Recommended background: mechanics, materials, physics, knowledge of a high-level computer programming language. Students cannot receive credit for this course if they have taken the Special Topics (ME 593J) version of the same course or ME 534.

ME 5311/MTE 511. Structure and Properties of Engineering Materials
(2 credits)

This course, (along with its companion course MTE 512 Properties and Performance of Engineering Materials), is designed to provide a comprehensive review of the fundamental principles of Materials Science and Engineering for incoming graduate students. In the first part of this 2-course sequence, the structure in materials ranging from the sub-atomic to the macroscopic including nano, micro and macromolecular structures will be discussed to highlight bonding mechanisms, crystallinity and defect patterns. Representative thermodynamic and kinetic aspects such as diffusion, phase diagrams, nucleation and growth and TTT diagrams will be discussed. Major structural parameters that effect of performance in materials including plastics, metallic alloys, ceramics and glasses will be emphasized. The principal processing techniques to shape materials and the effects of processing on structure will be highlighted. (Prerequisites: senior or graduate standing or consent of the instructor.) Note: Students cannot receive credit for this course if they have taken the Special Topics version of the same course (MTE 594S).

ME 5312/MTE 512. Properties and Performance of Engineering Materials
(2 credits)

The two introductory classes on materials science (MTE 511 and MTE 512) describe the structure-property relationships in materials. The purpose of this class is to provide a basic knowledge of the principles pertaining to the physical, mechanical and chemical properties of materials. The primary focus of this class will be on mechanical properties. The thermal, tensile, compressive, flexural and shear properties of metallic alloys, ceramics and glasses and plastics will be discussed. Fundamental aspects of fracture mechanics and viscoelasticity will be presented. An overview of dynamic properties such as fatigue, impact and creep will be provided. The relationship between the structural parameters and the preceding mechanical properties will be described. Basic composite theories will be presented to describe fiber-reinforced composites and nanocomposites. Various factors associated with material degradation during use will be discussed. Some introductory definitions of electrical and optical properties will be outlined. (Prerequisites: senior or graduate standing or consent of the instructor.) Note: Students cannot receive credit for this course if they have taken the Special Topics version of the same course (MTE 594P).

ME 5313. Introduction to Nanomechanics
(2 credits)

This course introduces students to nanomechanics. Topics covered include an introduction to mechanical systems, forces at the nano to atomic scales, cantilever theory, mechanics of 0D, 1D and 2D nanomaterials, polymer chain nanomechanics, molecular recognition, wear friction and adhesion at the nanoscale, scale dependence of frictional resistance, nano-indentation, surface elasticity and viscoelasticity mapping, lubrication principles at the nanoscale, interfacial forces in confined fluids, mechanics of electrorheological and magnetic fluids. Recommended Background: ME 4875 or consent of Instructor.

ME 5356/MTE 556. Smart Materials
(2 credits)

A material whose properties can respond to an external stimulus in a controlled fashion is referred to as a smart or intelligent material. These materials can be made to undergo changes modulus, shape, porosity, electrical conductivity, physical form, opacity, and magnetic properties based on an external stimulus. The stimuli can include temperature, pH, specific molecules, light, magnetic field, voltage and stress. These stimuli-sensitive materials can be utilized as sensors and as vehicles for the controlled delivery of drugs and other biomolecules in medical applications. Smart materials are also becoming important in other biological areas such as bio-separation, biosensor design, tissue engineering, protein folding, and microfluidics. The use of stimuli-sensitive materials is receiving increasing attention in the development of damage tolerant smart structures in aerospace, marine, automotive and earth quake

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resistant buildings. The use of smart materials is being explored for a range of applications including protective coatings, corrosion barriers, intelligent batteries, fabrics and food packaging. The purpose of this course is to provide an introduction to the various types of smart materials including polymers, ceramic, metallic alloys and composites. Fundamental principles associated with the onset of "smart" property will be highlighted. The principles of self-healable materials based on smart materials will be discussed. The application of smart materials in various fields including sensors, actuators, diagnostics, therapeutics, packaging and other advanced applications will be presented. Note: Students cannot receive credit for this course if they have taken the Special Topics version of the same course (MTE 594X).

ME 5358/MTE 558. Plastics
(2 credits)

This course will provide an integrated overview of the design, selection and use of synthetic plastics. The basic chemistry associated with polymerization and the structure of commercial plastics will be described. Various aspects of polymer crystallization and glass transition will be outlined. Salient aspects of fluid flow and heat transfer during the processing of plastics will be highlighted. Fundamentals of the diverse processing operations used to shape plastics and the resulting structures that develop after processing will be discussed. The mechanical behavior of plastics including elastic deformation, rubber elasticity, yielding, viscoelasticity, fracture and creep will be discussed. Plastic degradation and environmental issues associated with recycling and disposal of plastics will be examined. Typical techniques used in the analysis and testing of plastics will be described and a working knowledge of various terminologies used in commercial practice will be provided. Note: Students cannot receive credit for this course if they have taken the Special Topics version of the same course (MTE 594A).

ME 5361/MTE 561. Mechanical Behavior and Fracture of Materials
(2 credits)

The failure and wear-out mechanisms for a variety of materials (metals, ceramics, polymers, composites and microelectronics) and applications will be presented and discussed. Multi-axial failure theories and fracture mechanics will be discussed. The methodology and techniques for reliability analysis will also be presented and discussed. A materials systems approach will be used. (Prerequisites: ES 2502 and ME 3023 or equivalent, and senior or graduate standing in engineering or science.) Note: Students cannot receive credit for this course if they have taken the Special Topics version of the same course (MTE 593C/MTE 594C).

ME 5370/MTE 5841/MFE 5841. Surface Metrology
(3 credits)

This course emphasizes research applications of advanced surface metrology, including the measurement and analysis of surface roughness. Surface metrology can be important in a wide variety of situations including adhesion, friction, catalysis, heat transfer, mass transfer, scattering, biological growth, wear and wetting. These situations impact practically all the engineering disciplines and sciences. The course begins by considering basic principles and conventional analyses, and methods. Measurement and analysis methods are critically reviewed for utility. Students learn advanced methods for differentiating surface textures that are suspected of being different because of their performance or manufacture. Students will also learn methods for making correlations between surface textures and behavioral and manufacturing parameters. The results of applying these methods can be used to support the design and manufacture of surface textures, and to address issues in quality assurance. Examples of research from a broad range of applications are presented, including, food science, pavements, friction, adhesion, machining and grinding. Students do a major project of their choosing, which can involve either an in-depth literature review, or surface measurement and analysis. The facilities of WPI's Surface Metrology Laboratory are available for making measurements for selected projects. Software for advanced analysis methods is also available for use in the course. No previous knowledge of surface metrology is required. Students should have some background in engineering, math or science.

ME/AE 5380. Foundations of Elasticity
(2 credits)

This course is suitable as an introductory graduate level course. Topics will be chosen from the following: three-dimensional states of stress; measures of strain; thick-walled cylinders, disks and spheres; plane stress and plane strain; thermoelasticity; Airy stress function; energy methods, and exact theory for torsion of non-circular cross sections. This course may be taken independent of ME 5302. Students cannot receive credit for this course if they have taken the Special Topics (ME 593N) version of the same course or ME 531.

ME/AE 5381. Applied Elasticity
(2 credits)

This course is suitable as an introductory graduate level course. Topics covered will be chosen from the following: bending and shear stresses in unsymmetric beams; bending of composite beams; bending of curved beams; torsion of thin-walled noncircular cross sections; beams on elastic foundations; stress concentrations; failure criteria; stability of columns; and bending of plates. This course may be taken independent of ME 5301. Students cannot receive credit for this course if they have taken the Special Topics (ME 593N) version of the same course or ME 531.

ME 5383/CE 514. Continuum Mechanics
(2 credits)

This course covers the fundamentals of continuum mechanics at an introductory graduate level. Topics covered include: 1) Introduction: essential mathematics - scalars, vectors, tensors, and indicial notation; 2) Basics: three-dimensional states of stress, finite and infinitesimal measures strain, and principal axes; 3) Conservations laws: mass, linear momentum, angular momentum and energy; 4) Constitutive equations: ideal materials, Newtonian fluids, isotropy and anisotropy, elasticity and thermoelasticity, plasticity, and viscoelasticity; 5) Applications to classical problems and emerging topics in solid and fluid mechanics. Recommended background: undergraduate knowledge of strength of materials, fluid mechanics, and linear algebra.

ME 634. Holographic Numerical Analysis
(3 credits)

Recent advances in holographic analysis of body deformations are discussed. Included in the course are topics covering sandwich holography, optoelectronic fringe interpolation technique, theory of fringe localization, use of projection matrices and the fringe tensor theory of holographic strain analysis. The application of interactive computer programs for holographic analysis of engineering and biological systems will be outlined. Lectures are supplemented by laboratory demonstrations and experiments. (Prerequisites: Matrix algebra, vector calculus and consent of instructor.)

Design and Manufacturing:

ME 5401. Computer-Aided Design and Geometric Modeling
(2 credits)

This course covers topics in computer-aided geometric design and applications in mechanical engineering. The objectives of the course are to familiarize the students with complex geometric modeling and analytical techniques used in contemporary computer-aided design systems. Topics to be covered may include complex curve and surface generation, solid modeling, assembly and mechanism modeling, transformations, analytic geometry, offsets and intersections of complex shapes, graphics standards and data transfer, rendering techniques, parametric design and geometric optimization, numerical methods for geometric analysis and graphics design programming. Prerequisites: calculus, linear algebra, introductory computer programming, and ability to utilize a solid modeling CAD system. Students cannot receive credit for this course if they have taken the Special Topics (ME 593C) version of the same course or ME 545.

ME/MFE/MTE 5420. Fundamentals of Axiomatic Design of Manufacturing Processes
(2 credits)

The course starts with an in-depth study of axiomatic design. Applications of axiomatic design are considered primarily, although not exclusively, for the design of manufacturing processes and tools. Axiomatic design is a design methodology based on the premise that there are two axioms that apply to all good designs. These axioms facilitate the teaching and practice of engineering design as a scientific discipline. Manufacturing process analysis is considered from the perspective of supporting design. Methods of analysis of manufacturing processes with broad applicability are sought. Special attention is given to examples in machining (traditional, nontraditional and grinding), additive manufacturing, and to the production of surfaces. The ability to find commonalities across applications and generalize is emphasized to facilitate further development of principles with broad applicability. The content is delivered in video lectures and in readings from the technical literature. Homework and quizzes are given and delivered on-line. There is a project to design a manufacturing process. The topics can be from work or dissertations that can be interpreted as manufacturing processes and tools.

Credit cannot be given for this course and any of the similar, in-class versions for 3 credits, MFE 520, MTE 520 and ME 543.

ME 543/MFE 520/MTE 520. Axiomatic Design of Manufacturing Processes
(3 credits)

This course begins with elements axiomatic design, the theory and practice. Design applications are considered primarily, although not exclusively, for the design of manufacturing processes and tools. Axiomatic design is based on the premise that there are common aspects to all good designs. These commons aspects, stated in the independence and information axioms, facilitate the teaching and practice of engineering design as a scientific discipline. Analysis of processes and products is considered from the perspective of supporting product and process design. Fundamental methods of engineering analysis of manufacturing processes with broad applicability are developed. Attention is given to examples from one or more of the following: machining (traditional, nontraditional and grinding), additive manufacturing, and to the production of surface topographies. The ability to generalize from detailed examples is emphasized in order to facilitate the students' ability to development analyses and design methods with broader applicability.

This course is offered live, in-class only, to be completed in one semester, for three credits. Credit cannot be given for this course and any of the similar, on-line versions of this material for 2 credits: MFE521, MTE521 and ME521.

ME 5431/MFE 531. Computer Aided Manufacturing
(2 credits)

An overview of computer-integrated manufacturing (CIM). As the CIM concept attempts to integrate all of the business and engineering functions of a firm, this course builds on the knowledge of computer-aided design, computer-aided manufacturing, concurrent engineering, management of information systems and operations management to demonstrate the strategic importance of integration. Emphasis is placed on CAD/CAM integration. Topics include, part design specification and manufacturing quality, tooling and fixture design, and manufacturing information systems. This course includes a group term project. (Prerequisites: Background in manufacturing and CAD/CAM, e.g., ME 1800, ES 1310, ME 3820.) Note: Students cannot receive credit for this course if they have taken the Special Topics version of the same course (ME 593D/MFE 594D).

ME 5441/MFE 541. Design for Manufacturability
(2 credits)

The problems of cost determination and evaluation of processing alternatives in the design-manufacturing interface are discussed. Approaches for introducing manufacturing capability knowledge into the product design process are covered. An emphasis is placed on part and process simplification, and analysis of alternative manufacturing methods based on such parameters as: anticipated volume, product life cycle, lead time, customer requirements, and quality yield. Lean manufacturing and Six-Sigma concepts and their influence on design quality are included as well. Note: Students cannot receive credit for this course if they have taken the Special Topics version of the same course (MFE 594M).

Biomechanical Engineering:

ME 550/BME 550. Tissue Engineering
(3 credits)

This biomaterials course focuses on the selection, processing, testing and performance of materials used in biomedical applications with special emphasis upon tissue engineering. Topics include material selection and processing, mechanisms and kinetics of material degradation, cell-material interactions and interfaces; effect of construct architecture on tissue growth; and transport through engineered tissues. Examples of engineering tissues for replacing cartilage, bone, tendons, ligaments, skin and liver will be presented. (Recommended preparation: A first course in biomaterials equivalent to ME/BME 4814 and a basic understanding of physiology and cell biology.)

ME 552/BME 552. Tissue Mechanics
(3 credits)

This biomechanics course focuses on advanced techniques for the characterization of the structure and function of hard and soft tissues, and their relationship to physiological processes. Applications include tissue injury, wound healing, the effect of pathological conditions upon tissue properties and design of medical devices and prostheses. (Recommended preparation: A first course in biomechanics equivalent to ME/BME 4504.)

Other Activities:

ME 591. Graduate Seminar
(0 credits)

Seminars on current issues related to various areas of mechanical engineering are presented by authorities in their fields. All full-time mechanical engineering students are required to register and attend.

ME 593. Special Topics
(credits TBD)

Arranged by individual faculty with special expertise, these courses survey fundamentals in areas that are not covered by the regular mechanical engineering course offerings. Exact course descriptions are disseminated by the Mechanical Engineering Department well in advance of the offering. (Prerequisite: Consent of instructor.)

ME 598. Directed Research
(credits TBD)

For M.S. students wishing to gain research experience peripheral to their thesis topic, or for Ph.D. students wishing to gain research experience peripheral to their dissertation topic..

ME 599. Thesis Research
(credits TBD)

For master's students wishing to obtain research credit toward their thesis. (Prerequisite: Consent of Thesis Advisor.)

ME 693. Advanced Special Topics
(credits TBD)

Arranged by individual faculty with special expertise, these courses cover advanced topics that are not covered by the regular mechanical engineering course offerings. Exact course descriptions are disseminated by the Mechanical Engineering Department well in advance of the offering. (Prerequisite: Consent of instructor.)

ME 698. Pre-Dissertation Research
(credits TBD)

Intended for doctoral students wishing to obtain dissertation-research credit prior to admission to candidacy. (Prerequisite: Consent of Dissertation Advisor.)

ME 699. Dissertation Research
(credits TBD)

Intended for doctoral students admitted to candidacy wishing to obtain research credit toward their dissertations. (Prerequisite: Consent of Dissertation Advisor.)

Faculty

D.T. Petkie, Department Head and Professor; Ph.D., Ohio State University. Millimeter-wave and Terahertz sensing, spectroscopy, electromagnetic scattering and propagation, optics and imaging.

P. K. Aravind, Professor and Associate Head; Ph.D., Northwestern University. Quantum information theory.

N. A. Burnham, Associate Professor; Ph.D., University of Colorado. Mechanical properties of nanostructures, instrumentation for nanomechanics.

B. H. Currier, Assistant Teaching Professor, Ph.D., University of Massachusetts – Lowell. Health and medical physics, anatomical and functional diagnostic neutron imaging, radiation physics, nuclear materials.

F. A. Dick, Associate Teaching Professor, Ph.D., Worcester Polytechnic Institute. Nuclear and particle physics, astrophysics and planetary science.

G. S. Iannacchione, Professor; Ph.D., Kent State University. Soft condensed matter physics/ complex fluids, liquid-crystals, calorimetry, and order-disorder phenomena.

S. V. Kadam, Assistant Teaching Professor, Ph.D., University of Tuebingen, Germany. Cell migration, biophysics, microscopy, astro-biology.

R. P. Kafle, Assistant Teaching Professor, Ph.D., Worcester Polytechnic Institute. Experimental biophysics, fluorescence correlation spectroscopy, atom interferometers.

H. Kashuri, Assistant Teaching Professor, Ph.D., Northeastern University. Soft condensed matter, liquid crystal phases and phase transitions, electrical properties of human muscle.

D. C. Medich, Associate Professor; Ph.D., University of Massachusetts – Lowell. Nuclear science and engineering, medical and health physics, radiation biology.

M. B. Popovic, Assistant Research Professor, Ph.D., Boston University. Biomechanics and robotics, complex system dynamics, nuclear and particle physics.

R. S. Quimby, Associate Professor; Ph.D., University of Wisconsin – Madison. Optical properties of solids, laser spectroscopy, fiber optics.

L. R. Ram-Mohan, Professor; Ph.D., Purdue University. Field theory, many body problems, solid state physics, and finite-element modeling of quantum systems.

S. L. Rodriguez, Assistant Teaching Professor, Ph.D., University of Iowa, Iowa City, IA. Computational astrophysics/ astro-informatics, black hole thermo-dynamics, numerical general relativity, astrophysical detector characterization.

I. Stroe, Assistant Teaching Professor; Ph.D., Clark University. Experimental biophysics, protein structure, dynamic, and functionality.

L. Titova, Assistant Professor; Ph.D., University of Notre Dame. THz spectroscopy of biological materials, optical excitations and ultrafast carrier dynamics in nanomaterials, medical and biological applications of THz radiation, nanoparticles for biomedical imaging and photodynamic therapy

E. Tüzel, Associate Professor; Ph.D., University of Minnesota. Theoretical and computational biophysics, polymer physics, cell mechanics and cargo transport, complex fluids, soft-matter physics.

Q. Wen, Associate Professor, Ph.D., Brown University. Experimental biophysics, mechanical properties of tissue cells and biological materials, cell-ECM interactions.

K. Wu, Assistant Professor, Ph.D., New York University. Active matter, kinesin-driven microtubules, fluid dynamics, experimental biophysics.

A. Zozulya, Professor; Ph.D., Lebedev Physics Institute. Nonlinear optics, photorefractive materials, atom pipes.

Research Areas

The two major areas of research in the department are: Biophysics/Soft-Matter and Nanoscience/Condensed Matter Physics, including optics.

Nanoscience/Condensed Matter

Cold atoms – Bose-Einstein Condensation of bosons and fermions, atom wave guides and interferometers.

Magnetic Solids – Magnetic impurities in semiconductors: diluted magnetic semiconductors and the onset of ferromagnetism in spintronic materials.

Nanomechanics – Mechanical properties of nanostructures, instrumentation and metrology for nanomechanics.

Photonics – Nonlinear optics, fiber optics, optical properties of rough surfaces and of thin metal films. Development of infrared fiber lasers and materials, mid-IR and FIR quantum cascade laser design.

Quantum Information – Foundations of quantum mechanics, quantum algorithms.

Semiconductors – Optical properties of super-lattices, heterostructure laser design, spintronics in diluted magnetic semiconductors,devices.

Spectroscopy – Laser spectroscopy of impurity ions in glasses, quasi-elastic/ inelastic light scattering and excitation/ modulation spectroscopy of super-lattices, thin films, surface phenomena.

Ultrafast optical spectroscopy – Terahertz science and technology, optical properties of nanomaterials for energy conversion.

Wavefunction Engineering – Nanostructures, finite-element modeling of quantum systems and wells, field theory.

Biophysics/Soft-Matter

Biomaterials – hydration effects on protein dynamics, thermodynamics of proteins and DNA, self-assembly of biomaterials, dielectric relaxation spectroscopy, relaxation calorimetry, resonant ultrasound spectroscopy, studies of tissue cells, theory and simulations of bio-polymers and molecular motors.

Biomechanics – Locomotion of living organisms, cellular structure and motion, computational biophysical fluid dynamics.

Cellular biophysics – Cell mechanics and intra-cellular transport, physics of the cytoskeleton (cellular skeleton), cargo transport in cells, super-resolution imaging, correlation spectroscopy, simulations of cellular processes.

Complex Fluids – Diffusion and transport properties of complex fluids, light scattering spectroscopy of liquids and polymer melts, mesoscale simulations of liquids, capillary wave theory, theory and simulations of phase transitions in multi-component mixtures, active fluids.

Glasses – Theory and simulation, thermodynamics and relaxation dynamics.

Liquid Crystals – Thermotropic/ lyotropic/ colloidal systems, phase transitions and critical phenomena, cooperative behavior and self-assembly, quenched random disorder effects, calorimetry instrumentation.

Polymers – Molecular properties at the single molecule level, polymer and bio-macromolecular solutions, surfactants, colloids.

Program of Study

The Department of Physics offers the M.S. and Ph.D. in Physics, a program leading to a degree of Master of Science in Physics for Educators (MPED), and a Graduate Certificate in Nuclear Science and Engineering (NSE). WPI undergraduates can enroll in an accelerated B.S./M.S. program. Research opportunities are available in experimental and theoretical/ computational studies of biophysics/soft-matter and nanoscience/condensed matter physics, including optics.

WPI physics graduate program prepares students for careers in research in either an academic or industrial setting. Prospective employers are industrial laboratories, government or non-profit research centers, as well as colleges or universities. Professional development opportunities for career pathways in industry, academia, and education are available in the Physics Department and offered by the WPI Graduate Studies office.

The Physics program reserves its financial aid for graduate students in the Ph.D. program.

Master of Science in Physics (M.S.)

This program gives students a broad background in physics, placing an emphasis on not only core areas, but also high demand subject areas such as biophysics and nanoscience. In addition to core courses, students are encouraged to acquire breadth by choosing special topics courses that complement their studies. All experimental and theoretical research areas are available for the M.S. in Physics degree. Opportunities to mentor undergraduate students exist, given the rich project-based curriculum WPI offers. Students have a choice of completing their master's thesis or passing the Comprehensive Written Examination (CWE) to obtain their degree. The program provides a suitable foundation for the pursuit of a Ph.D. degree in physics, or a related field, or for a career in industry immediately after graduation.

Master of Science in Physics for Educators (MPED)

The Master of Science in Physics for Educators is designed specifically for middle school, high school, and community college in-service educators. The emphasis of the program is put on physics courses designed for educators and is combined with courses in assessment and evaluation theory and a participant-designed project. The physics content courses are intended to give educators a deep but applicable understanding of physics that makes advanced physics topics easily accessible to educators and the students they teach. Topics covered will include modern physics, methods in physics and physics for citizens and leaders. Support for degree candidates extends beyond the specific coursework and projects as participants will become part of a network of physicists which ranges from local individuals to a much broader community. The program may be used to help middle and high school educators move from Initial to Professional Licensure in Massachusetts. For information about admissions and requirements, see the listing under STEM for Educators.

Doctor of Philosophy in Physics (Ph.D.)

Faculty research focuses on both experimental and computational/ theoretical work with particular emphasis on biophysics and nanoscience. Our Ph.D. students are immersed in a stimulating collaborative and interdisciplinary community of fellow researchers and engaged faculty focused on real-world problems. In addition to research, professional development is an integral part of our Ph.D. curriculum. Ph.D. students interested in an academic career mentor undergraduate students, teach undergraduate laboratories, and are trained to become effective teacher-scholars in the classroom. Faculty-initiated internship opportunities exist at other institutions, national laboratories, and industrial partners. Students are also trained in scientific and technical writing, as well as proposal development.

Graduate Certificate in Nuclear Science and Engineering (NSE)

The Graduate Certificate in Nuclear Science & Engineering requires the successful completion of four courses (12 graduate credits) with an overall GPA of 3.0. Credits are chosen from the NSE510-50 course listing or by approval of the NSE Program Committee. Courses cover such topics as nuclear power, radioactivity, chain reaction physics, nuclear reactor safety, power plant design and operation, and case studies of nuclear accidents. These courses are offered on campus, and online through Corporate and Professional Education. The faculty in the certificate program hold a full-time position in a WPI academic department or are affiliated faculty approved by an academic department and NSE program review committee.

Combined B.S./M.S. Program

This program allows a student to work concurrently toward bachelor and master of science degrees in physics.

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Admission Requirements

M.S. and Ph.D. Physics Programs

B.S. in Physics or the equivalent is required. For the combined B.S./M.S. program, students must be currently enrolled as WPI undergraduates in Physics. Students applying to the Ph.D. program are required to submit GRE Physics Subject test scores. This requirement is waived for applicants with an M.S. degree in Physics (or a related field, subject to the approval of the Physics Department Graduate Committee). The application should also include a Statement of Purpose describing the motivation for pursuing a graduate degree in physics at WPI, and identifying one or more faculty members as potential research advisors. To learn more about a faculty's research, contact them directly.

MPED and NSE Programs

B.S. in Physics preferred. However, applicants with comparable backgrounds will also be considered.

Degree Requirements

For the M.S.

The M.S. degree in physics requires 30 semester hours of credit: 6 or more in thesis or directed research with the remainder in approved courses and independent studies, to include PH 511, PH 514, PH 515, PH 522 and PH 533 (15 semester hours). All full-time students are required to register for the zero-credit graduate seminar (PH 580) every term. The thesis option requires the completion and defense of an M.S. thesis as well as a public seminar presentation based on the thesis research. This option also requires a thesis committee formed by the end of the first year by the student and the research advisor, with the approval of the *Physics Department Graduate Committee* (PDGC). The committee will consist of three faculty members (including the advisor), will be responsible for overseeing the progress of the student towards a successful completion of their degree, and provide mentoring. The non-thesis option requires students register for and pass the *Comprehensive Written Examination* (PH 798).

For the Master of Science in Physics for Educators (MPED)

For a complete overview of degree requirements, please see STEM for Educators.

For the Ph.D.

The doctor of philosophy degree requires 90 credit hours, including 42 in approved courses or directed study (which must include PH 511, PH 514-515, PH 522 and PH 533, or their equivalents), 30 of dissertation research, and completion and defense of a Ph.D. thesis. Courses taken to satisfy M.S. degree requirements may be counted against the required 42 credits of courses, but completion of a M.S. degree is not required.

All full-time students are required to register for the zero-credit graduate seminar (PH 580) every term. Upon approval of the Physics Department Graduate Committee (PDGC), a maximum of 1/3 of the credit requirements outlined above may be satisfied by transferring graduate courses completed at other accredited, degree-granting institutions, provided they were not used to satisfy degree requirements elsewhere. Students entering with M.S. degrees may be required to take some or all of the core courses as part of their total 60 credits requirement, as determined by the PDGC upon review of the M.S. coursework.

The PDGC reviews each student's academic work on an annual basis, and the committee and the academic or research advisor may require additional coursework to address specific deficiencies in the student's background. Students must maintain a minimum of a 3.0 GPA to be in good standing. One year of residency in the program is required.

A brief description of other Ph.D. program requirements follows below.

Comprehensive Written Examination

Students entering the Ph.D. program are required register for and pass the *Comprehensive Written Examination* (PH 798) no later than the end of their second year (no more than 3 attempts allowed). This exam is designed to test a student's comprehension of core physics curriculum, and is prepared, administered and evaluated by the PDGC. It is offered twice a year, during Fall and Spring semesters.

Ph.D. Qualifying Examination

No later than the end of the third year after formal admittance to the Ph.D. program, students are required to register for and pass a *Ph.D. Qualifying Exam* (PH 799) in which the students are required to write and defend an original research proposal before a committee representative of the area of their specialization, approved and appointed by the PDGC. The students are allowed only two attempts to pass this exam. The examination is used to evaluate the ability of the student to pose meaningful scientific questions, to propose experimental or theoretical methods for answering those questions, and to interpret the validity and significance of probable outcomes of these theoretical conjectures, models or experiments. The committee will consist of a minimum of three physics faculty members including the advisor, and at least one faculty member from outside the department, and will administer and evaluate the exam. The research advisor cannot be the chair of this committee. The students are also required to take and pass a one-credit scientific writing course (PH 585) prior to their first attempt at taking the Ph.D. Qualifying Exam.

Ph.D. Dissertation

To fulfill the final Ph.D. degree requirement, the candidate must submit and defend a satisfactory dissertation to the dissertation committee formed in consultation with the research advisor, and approved by the PDGC. This committee will consist of a minimum of three physics faculty members including the advisor, and at least one faculty member from outside the department. The research advisor cannot be the chair of this committee.

Course Descriptions

All courses are 3 credits unless otherwise noted.

Note: Students must maintain a minimum of a 3.0 GPA to be in good standing.

PH 500. Independent Study (ISG)

(credits are arranged: 1-3)

Various specialized topics and/or research areas from one to two graduate students. Arranged individually with the faculty.

PH 511. Classical Mechanics

Lagrangian and Hamiltonian formulations. Rigid body motion. Poisson brackets, Hamilton-Jacobi theory. (Prerequisite: B.S. in physics or equivalent.)

PH 514. Quantum Mechanics I
Schrodinger wave equation, potential wells and barriers, harmonic oscillator, hydrogen atom, angular momentum and spin. (Prerequisite: B.S. in physics or equivalent.)

PH 515. Quantum Mechanics II
Perturbation theory, scattering theory, Born approximation, quantum theory of radiation, the Dirac equation. (Prerequisite: PH 514.)

PH 522. Thermodynamics and Statistical Mechanics
Ensemble theory; canonical, microcanonical, and grand canonical ensembles. Quantum statistical mechanics, Bose-Einstein and Fermi-Dirac statistics. (Prerequisite PH 511.)

PH 533. Advanced Electromagnetic Theory
Classical electrodynamics including boundary-value problems using Green's functions. Maxwell's equations, electromagnetic properties of matter, wave propagation and radiation theory. (Prerequisite: B.S. in physics or equivalent.)

PH 554. Solid State Physics
Phonons and specific heat of solids; electronic conductivity and band theory of solids; Fermi and Bose gases; magnetic interactions. (Prerequisite: PH 514.)

PH 561 Atomic Force Microscopy.
Atomic force microscopes (AFMs) are instruments that allow three-dimensional imaging of surfaces with nanometer resolution and are important enabling tools for nanoscience and technology. The student who successfully completes this course will understand the functional principles of AFMs, be able to run one, and interpret the data that are collected. The recommended background for this course is a bachelor's degree in science or engineering. Students who have successfully completed PH 2510, the undergraduate version of this course, may not earn credit for PH 561.

PH 562. Fundamentals of Biological Physics
The course will cover the fundamental concepts of biological physics. The main objective is to learn how to apply the principles of physics, methods of mathematical analysis and computational modeling to complex biological systems and develop a better understanding. The approach will be truly interdisciplinary, bringing concepts from statistical physics, classical mechanics, cell biology, chemistry and biochemistry. Topics covered include: biology by the numbers: time and length scales, mechanical and chemical equilibrium in the living cell, entropy in biology, two-state systems and cooperative binding, random walks and the structure of macromolecules, architecture of the cytoskeleton, biological membranes, modeling of fluids, statistical view of biological dynamics, life in crowded environments, rate equations and dynamics in the cell, dynamics of molecular motors. (Prerequisite: A bachelor's degree in physics, biology, chemistry, or engineering.)

PH 572. Nanoscience Journal Club
(1 credit)
Students interested in nanoscience read journal articles, write abstracts, give short talks, engage in critical discussion, and provide feedback to fellow students. The objectives of the course are for students to learn about current topics in nanoscience and nanotechnology and to improve their professional skills. (Prerequisite: A bachelor's degree in physics, biology, chemistry, or engineering.)

PH 580. Graduate Seminar
(0 credits)
Students attend Physics Colloquia by WPI faculty and invited scientists on current research topics in different areas of physics. They discuss results and ideas presented in those talks. In addition, students give presentations on their research or on problems of current interest to physics community. The course therefore will provide opportunities for students to develop their presentation skills, broaden their perspectives and provide networking opportunities. All full-time physics graduate students are required to register and attend.

PH 585. Scientific Writing and Proposal Development
(1 credit)
This course will cover key elements of writing successful grant or fellowship proposals, as well as manuscripts. The topics that will be covered will include project development, identification of funding agencies or journals, proposal and manuscript writing and editing, as well as aspects of the submission and review process. Students will be expected to develop a proposal, and participate in reviews. Students are expected to complete this course prior to taking the Ph.D. Qualifying Exam in Physics. Recommended background: A bachelor's degree in science, technology, engineering, or mathematics.

PH 597. Special Topics
(1-3 credits)
Arranged by physics faculty for individual or groups of students, these offerings cover topics that are not covered by the regular Physics course offerings. Exact course descriptions are posted by the faculty in advance of the offering. (Prerequisite: Consent of instructor)

PH 598. Directed Research
(credit varies)
A directed and coherent program of research that, in most cases, will eventually lead to thesis or dissertation research. This is also used for Directed Research Rotation (for 3 credit hours) for first year students who have not yet taken the Qualifying Examination in order to explore the available research opportunities.

PH 599. M.S. Thesis Research
(credit varies)
Each student will work under the supervision of a member of the department on the thesis research for their Master of Science in Physics degree. (Prerequisite: Consent of advisor)

PH 699. Ph.D. Dissertation
(credit varies, no more than 30 credits)
Can be taken any time after passing the Physics Qualifying Examination but required in the last semester for the writing and defending of the Ph.D. dissertation. (Prerequisite: Consent of advisor)

PH 798. Comprehensive Written Examination
(0 credit)
Comprehensive Written Examination prepared, administered and evaluated by the Physics Department Graduate Committee (PDGC). Recommended background: Student should be enrolled in the Physics Graduate program, either seeking an M.S. degree with no-thesis option, or a Ph.D. degree.

PH 799. Ph.D. Qualifying Examination
(0 credit)
Students are required to write and defend an original research proposal before a committee representative of the area of their specialization, approved and appointed by the Physics Department Graduate Committee (PDGC). Recommended background: Student should be enrolled in the Physics Graduate program, seeking a Ph.D. degree.

MPE 510. Classical Mechanics
(2 credits)
Broad coverage emphasizing interconnections of a mechanical description of the universe utilizing both algebraic and calculus language at a level appropriate for secondary school educators. Topics include: vectors and vector manipulation to describe motion, Newton's laws of motion; work and energy concepts; energy and momentum conservation laws; models of forces and interactions; generalized coordinates and momentum; overview of Lagrangian and Hamiltonian formulations.

MPE 520. Electrodynamics
(2 credits)
Broad coverage at the appropriate level emphasizing interconnections of the electromagnetic interactions in the universe utilizing both algebraic and calculus language at a level appropriate for secondary school educators. Topics include: electro and magneto statics and dynamics, boundary-value problems; Maxwell's equations; overview of electromagnetic properties of matter and wave propagation (radiation).

MPE 530. Modern Physics
(2 credits)
Broad coverage of the three central areas of modern physics that emphasize the wonder and interconnections at the conceptual level appropriate for secondary school educators. Topics include: Quantum Physics (postulates, Schrödinger and Dirac formalisms, implications and interpretations), Special and Introduction to General Relativity (the four-vector, space-time, invariants, time dilation and length contraction), and Thermo/Statistical Physics (macroscopic variables, equation of state, state functions, response functions, microscopic variables, statistical approach, ensembles, the partition function).

MPE 540. Differential Equations in Nature
(2 credits)

Emphasizes connections and interconnections with the mechanical, electromagnetic, and modern areas as well as mathematical areas of oscillations, waves, and optics utilizing differential equations at a level appropriate for secondary school educators. Topics include: Free, damped, and driven-damped oscillations, waves, Doppler Effect, optics, interference and diffraction. Examples are drawn from a wide range of physical phenomena to illustrate each concept. To develop this content, homogeneous and non-homogeneous differential equations of the first and second order will be employed. Thick contextual meaning will be drawn to support mathematical foundation and vice versa to allow for deeper "authentic" learning.

MPE 550. Computational Methods in Physics
(2 credits)

Topics are chosen to illustrate various numerical techniques useful for educators and students to illustrate physics concepts and develop a sense of physical intuition through simulations and modeling. It is not intended to be a course on numerical methods; rather it will be aimed at the application of numerical methods to physical models. Various programming languages/platforms are utilized in each example to highlight the general nature and to provide choices matching students programming backgrounds.

MPE 560. Experimental Methods in Physics
(2 credits)

Hands-on methods of physically testing concepts and models of the universe. Technology is utilized but general methods accessible to barely outfitted lab environments are stressed. Topics covered are in a series of subject units, the physical principles underlying the phenomena to be observed and the basis for the measurement techniques employed is reviewed. Principles and uses of standard laboratory instruments (oscilloscopes, meters for frequency, time, electrical and other quantities, lock-in amplifiers, etc.) are stressed. In addition to systematic measurement procedures and data recording, strong emphasis is placed on processing of the data, preparation and interpretation of graphical presentations, and analysis of precision and accuracy, including determination and interpretation of best value, measures of error and uncertainty, linear best fit to data, and identification of systematic and random errors. Preparation of high-quality experiment reports is also emphasized. Representative experiment subjects are: mechanical motions and vibrations; free and driven electrical oscillations; electric fields and potential; magnetic materials and fields; electron beam dynamics; optics; diffraction-grating spectroscopy; radioactive decay and nuclear energy measurements.

MPE 572. Physics Research Experience for Teachers
(3 credits)

Provides educators with hands-on research experience either in the research programs in Physics at WPI or other venues but under the oversight of the physics faculty. The goal is to support the active involvement of educators in research in order to translate their research experience into new classroom activities and build long term collaborative relationships between the researcher(s), educator(s), and potentially the educator(s') students. Research activities can range from experimental to theoretical to computational and can involve multiple educators and/or their students with some expectation that the activity may lead to a publication.

MPE 574. Physics for Citizens and Leaders
(3 credits)

Emphasizes physics concepts and connections to society. Educators will explore and understand the important connections between society and the relevant physics concepts and their context. The goal is for the educator to be able to apply critical thinking of the application of physics to important societal issues. Topics can range from energy options, climate change, technology assessment and risk, ethical use of science.

MPE 576. Physics in Popular Culture
(3 credits)

Covers myths and misconceptions of physics in popular culture (i.e. movies, books, TV, web, etc.). The goal of this independent study is for the educator to be able to identify how the representation of physics in popular media perpetuates important myths and misconceptions that impact reasoning and critical thinking, sometimes in a profoundly negative way. Emphasis is placed on utilizing these representations as teaching/learning moments for the specific relevant physical concepts.

NSE 510. Introduction to Nuclear Science and Engineering

This introductory course provides an overview of the field of nuclear science and engineering as it relates to nuclear power and nuclear technologies. Fundamental concepts relevant to nuclear systems are introduced, including radioactivity, radiation interaction phenomena, chain reaction physics, and transport in engineering materials. Nuclear reactor physics and design concepts are introduced with focus on light water fission reactors. A survey of advanced nuclear technologies and applications is provided. Prerequisites: graduate or senior standing or consent of the instructor.

NSE 520. Applied Nuclear Physics

This course introduces engineering and science students to the fundamental topics of nuclear physics for applications, basic properties of the nucleus, nuclear radiations, and radiation interactions with matter. The course is divided into four main sections: (1) introduction to elementary quantum mechanics, (2) nuclear and atomic structure, (3) nuclear decays and radiation, and (4) nuclear matter interactions and nuclear reactions. Prerequisites: Physics of mechanics and electrodynamics (PH1110/11 and PH1120/21) and mathematical techniques up to and including ordinary differential equations (MA2051)

NSE 530. Health Physics

This course builds on fundamental concepts introduced in NSE510 and applies them to key topics in health physics and radiation protection. Health physics topics include man-made and natural sources of radiation, dose, radiation biology, radiation measurement, and radiation safeguards. Radiation protection concepts are explored as they apply to existing and advanced nuclear power generators, including reactor safety, nuclear waste and byproducts, regulatory constraints, and accident case studies. Prerequisites: graduate standing or consent of the instructor

NSE 540. Nuclear Materials

This course applies fundamental materials science concepts to effects on materials in harsh nuclear environments. An overview is provided on environments, special nuclear materials, and constraints in materials selection. Relationships are developed between nuclear effects on crystal structure, microstructure, degraded material performance, and bulk properties of engineering and electronic materials. Case studies provide examples of enhancements induced my multiple harsh environments and mitigation through material design hardening. Prerequisites: ES2001 or equivalent.

NSE 550. Reactor Design, Operations, and Safety

This course provides a systems engineering view of commercial nuclear power plant technology. Power plant designs and their evolutions are studied, ranging from early to modern generation light water reactors, as well as advanced designs families, such alternate moderator and breeder reactors. Critical aspects of conventional power reactor designs are explored in detail, including steam supply, reactor core, control, and protection systems. Plant operational characteristics are studied, including reactor dynamics, control, feedback, and fuel cycle management. Critical power plant safety aspects of the design and operations are explored and reinforced with lessons learned from major power generator accidents scenarios (including Three Mile Island, Chernobyl, and Fukushima Daiichi). Prerequisites: graduate standing or consent of the instructor

NSE 595. Special Topics
(1-3 credits)

Arranged by faculty affiliate to the Nuclear Science and Engineering program for individual or groups of students, these courses survey areas that are not covered by the regular NSE course offerings. Exact course descriptions are disseminated by the NSE Program Committee well in advance of the offering. (Prerequisite: Consent of instructor.)

Robotics Engineering

www.wpi.edu/academics/robotics/

Faculty

M. A. Gennert, Professor, Robotics Engineering Program Director; Sc.D., Massachusetts Institute of Technology 1987. Image processing, image under standing, artificial intelligence, robotics.

S. Barton, Assistant Professor; Ph.D. University of Virginia, 2012. Human-robot interaction in music composition and performance, design of robotic musical instruments, music perception and cognition, audio production.

N. Bertozzi, Senior Instructor; M.S. Northeastern University. Engineering design graphics, active learning/flipped classrooms, program and course student outcomes assessment.

C. A. Brown, Professor; Ph.D., University of Vermont, 1983. Surface metrology, machining, grinding, mechanics of skiing, axiomatic design.

D. Cyganski, Professor; Ph.D., Worcester Polytechnic Institute. Optimization and security of Internet communications, distributed and fault-tolerant computing, CORBA, machine vision, automatic target recognition.

R. J. Duckworth, Associate Professor; Ph.D., Nottingham University. Embedded computer system design, computer architecture, real-time systems, wireless instrumentation, rapid prototyping, logic synthesis.

L. Fichera, Visiting Assistant Professor; Ph.D., University of Genoa/Italian Institute of Technology. Computer- and robot-assisted surgery, continuum medical robots, machine learning.

G. Fischer, Associate Professor, Ph.D., Johns Hopkins University. Medical robotics, computer assisted surgery, robot control, automation, sensors and actuators.

J. Fu, Assistant Professor; Ph.D., University of Deleware, 2013. Control theory, formal methods, machine learning.

C. Furlong, Associate Professor; Ph.D., Worcester Polytechnic Institute. MEMS and MOEMS, nanotechnology, mechatronics, laser applications, holography, computer modeling of dynamic systems.

A. H. Hoffman, Professor; Ph.D., University of Colorado. Biomechanics, biomaterials, biomedical engineering, rehabilitation engineering, biofluids, continuum mechanics.

X. Huang, Professor; Ph.D., Virginia Tech. Reconfigurable computing, VLSI integrated circuits, networked embedded systems.

Z. Li, Assistant Professor; Ph.D., University of California, Santa Cruz, 2014. Motion control, haptics, exoskeletons, biomechanics, medical robotics.

F. J. Looft, Professor; Ph.D., Michigan. Instrumentation, digital and analog systems, signal processing, biomedical engineering, microprocessor systems and architectures, space-flight systems.

W. R. Michalson, Professor; Ph.D., Worcester Polytechnic Institute. Satellite navigation, real-time embedded computer systems, digital music and audio signal processing, simulation and system modeling.

C. Onal, Assistant Professor; Ph.D. Carnegie Mellon University, 2009. Soft robotics, printable robotics, bio-inspiration, control theory, micro/nano-robotics.

C. Pinciroli, Assistant Professor, PhD., Université Libre de Bruxelles, Belgium, 2014. Swarm robotics, software engineering, multi-agent systems, human-swarm interaction, programming languages.

M. B. Popovic, Assistant Research Professor; Ph.D. Boston University. Human neurosensory-motor organization, soft robotics, wearable robotics, assistive robotics, human augmentation systems.

C. B. Putnam, Senior Instructor, Robotics Engineering Program Associate Director, M.S. Penn State University. Robotics systems design, industrial robotics.

C. Rich, Professor; Ph.D., Massachusetts Institute of Technology. Artificial intelligence and its intersections with human-computer interaction, interactive media & game development, robotics, intelligent tutoring systems, knowledge-based software tools.

C. L. Sidner, Research Professor; Ph.D., Massachusetts Institute of Technology, 1979. Discourse processing, collaboration, human-robot interaction, intelligent user interfaces, natural language processing, artificial intelligence.

J. Skorinko, Associate Professor; Ph.D. University of Virginia, 2007. Social psychology, decision-making, interpersonal interactions.

K. A. Stafford, Teaching Professor, Robotics Resource Center Director, Robotics Engineering Program Associate Director; M.S., Air Force Institute of Technology. Robotics systems design.

A. M. Wyglinski, Associate Professor; Ph.D., McGill University. Wireless communication systems engineering, vehicular technology, cognitive radio, software-defined radio, autonomous vehicles, wireless spectrum, vehicular security, cyber-physical systems.

Program of Study

M.S. Program

The Robotics Engineering Program offers the M.S. degree with thesis and non-thesis (course-work only) options. The program strives to educate men and women to:

- Have a solid understanding of the fundamentals of Computer Science, Electrical and Computer Engineering, Mathematics, and Mechanical Engineering underlying robotic systems.
- Have an awareness of the management and systems contexts within which robotic systems are engineered.
- Develop advanced knowledge in selected areas of robotics, culminating in a capstone research or design experience.

Admission Requirements

Students will be eligible for admission to the program if they have earned an undergraduate degree in Computer Engineering, Computer Science, Electrical Engineering, Mechanical Engineering or a related field from an accredited university consistent with the WPI graduate catalog. Admission will also be open to qualified WPI students who opt for a five-year Bachelors-Masters

program, with the undergraduate major in Computer Science, Electrical & Computer Engineering, Mechanical Engineering, Robotics Engineering or a related field. Admission decisions will be made by the Robotics Engineering Graduate Program Committee based on all of the factors presented in the application.

Degree Requirements

For the M.S.

The M.S. program in Robotics Engineering requires 30 credit hours of work. Students may select a non-thesis option, which requires a 3-credit capstone design/practicum, or a thesis option which requires a 9-credit thesis. All entering students must submit a plan of study identifying the courses to be taken and a prospective project topic before the end of the first semester in the program. The plan of study must be approved by the student's advisor and the RBE Graduate Program Committee, and must include the following minimum requirements:

1. **Robotics Core (15 credits)***
   - **Foundations (9 credits)**
     RBE 500 Foundations of Robotics
     RBE/ME 501 Robot Dynamics
     RBE 502 Robot Control
   - **Core (6 credits)**
     Any RBE 500+ other than the above.
     (*) *At least 15 credits are needed. Any additional credits accrued from these courses will be counted as Electives.*
2. **Engineering Context (3 credits):**
   3 credits hours selected from the following courses:
   ETR 500 Entrepreneurship and Innovation
   ETR 593 Technology Commercialization: Theory, Strategy and Practice
   MIS 576 Project Management
   OBC 501 Interpersonal and Leadership Skills
   BUS 546 Managing Technological Innovation
   Courses prefixed by SYS at the 500 level or above.
3. **Capstone/Thesis (3-9 credits):**
   A 3 credit hour capstone experience or a 9 credit hour thesis.
4. **Electives (3-9 credits):**
   Sufficient course work selected from courses at the 500 level or above in Science, Engineering, or Business to total 30 credit hours with the approval of the student's advisor on the Plan of Study. Courses at the 4000 level may also be taken as electives in exceptional circumstances with the additional prior approval of the RBE Graduate Committee.

Thesis Option

The M.S. thesis consists of 9 credit hours of work, normally spread over at least one academic year. A thesis committee will be set up during the first semester of thesis work. This committee will be selected by the student in consultation with the major advisor and will consist of the thesis advisor, who must be a full-time WPI RBE faculty member, and two other faculty members, at least one of whom is a WPI RBE faculty member, whose expertise will aid the student's research program. An oral presentation before the Thesis Committee and a general audience is required. In addition, all WPI thesis regulations must be followed.

Non-Thesis Options

As an alternative to a 9-credit research-based thesis, students may elect a 3-credit capstone from the following options:

- Capstone Project Experience in Robotics Engineering (RBE 594),
- Robotics Engineering Practicum (RBE 596), or
- Directed Research (RBE 598).

All of the non-thesis options must demonstrate significant graduate-level work involving Robotics Engineering, include substantial analysis and/or design, and conclude with a written report and presentation.

The Capstone Project Experience in Robotics Engineering (RBE 594) is a project-based course that integrates theory and practice, and provides the opportunity to apply the skills and knowledge acquired in the Robotics Engineering curriculum. The project is normally conducted in teams of two to four students. Students are encouraged to select projects with practical significance to their current and future professional responsibilities. The projects are administered, advised, and evaluated by WPI faculty as part of the learning experience, but students are also encouraged to seek mentorship from experienced colleagues in the Robotics Engineering profession.

The Robotics Engineering Practicum (RBE 596) provides students an opportunity to put into practice the principles that have been studied in previous courses. It will generally be conducted off campus and will involve a real-world robotics-engineering situation. Overall conduct of the practicum will be supervised by a WPI RBE faculty member; an on-site liaison will direct day-to-day activity. For a student from industry, the practicum may be sponsored by his or her employer. The project must include substantial analysis and/or design related to robotics engineering and will conclude with a substantial written report submitted to the advisor and on-site liaison.

The Directed Research (RBE 598) option provides a research-oriented means to satisfy the capstone requirement. The student and research advisor will agree on the specific topics and deliverables on a per-project basis. The project must include substantial research, analysis and/or design related to robotics engineering and will conclude with a substantial written report and public presentation.

Transfer Credit

A student may petition for permission to use graduate courses taken at other accredited, degree-granting institutions to satisfy RBE graduate degree requirements. A maximum of 12 graduate credits, with a grade of B or better, may be satisfied by courses taken elsewhere and not used to satisfy degree requirements at other institutions. Petitions are subject to approval by the RBE Graduate Committee, and are then filed with the Registrar. Transfer credit will not be allowed for undergraduate-level courses taken at other institutions. In general, transfer credit will not be allowed for any WPI undergraduate courses used to fulfill undergraduate degree requirements; however, note that there are exceptions in the case of students enrolled in the B.S./M.S. program.

A student with one or more WPI master's degrees who is seeking an RBE master's degree from WPI may petition to apply up to 9 prior credits toward satisfying requirements for the subsequent degree. Petitions are subject to approval by the RBE Graduate Committee.

Students who take graduate courses at WPI prior to formal admission to the RBE graduate program may petition to apply up to 9 graduate credits to fulfill the RBE graduate degree requirements. Once again, petitions are subject to approval by the RBE Graduate Committee.

For the Ph.D.

The Ph.D. program in Robotics Engineering strives to educate men and women to:

- Have an advanced understanding of the Computer Science, Electrical and Computer Engineering, Mathematics, and Mechanical Engineering underlying robotic systems.
- Apply tools and concepts from Management and Systems Engineering to realize robotics systems and exercise professional leadership.
- Make significant research contributions in selected areas of robotics.

Admission Requirements

Students will be eligible for admission to the program if they have earned an undergraduate or graduate degree in Computer Engineering, Computer Science, Electrical Engineering, Mechanical Engineering, Robotics Engineering, or a related field from an accredited university. Applicants must supply a Statement of Purpose, three Letters of Recommendation, and Graduate Record Examination scores. The GRE requirement may be waived for WPI students and alumni, or at the discretion of the Robotics Engineering Graduate Program Committee when supplied with additional supporting materials such as published papers or a record of work experience. Admission decisions will be made by the Robotics Engineering Graduate Program Committee based on all of the information presented in the application.

Degree Requirements

The Ph.D. program in Robotics Engineering requires 60 credit hours of work beyond the M.S. degree or 90 credit hours beyond the B.S degree. Coursework must include 3 credit hours of Management or Systems Engineering courses at the 500 level or above. This requirement may be satisfied as part of the M.S. in Robotics Engineering or other M.S. program. All entering students must submit a plan of study identifying the courses to be taken and a prospective research area before completing more than 9 graduate credits. The plan of study must be approved by the student's academic advisor and submitted to the RBE Graduate Program Committee, and must include the following minimum requirements:

For students entering with an M.S., the 60 credits shall be distributed as follows:

1. Coursework, including Special Topics and Independent Study (12 credits). If not already included in the M.S. degree, the credits must include 3 credit hours of Management courses at the 500 level or above, or 3 credit hours of Systems Engineering courses at the 500 level or above.
2. RBE 699 Dissertation Research (30 credits).
3. Other. Additional coursework, Independent Study, RBE 598 Directed Research or RBE 699 Dissertation Research (18 credits).

For students entering with a B.S., the 90 credits shall be distributed as follows:

1. RBE M.S. Degree Requirements (30 credits).
2. Coursework, including Special Topics and Independent Study (12 credits).
3. RBE 699 Dissertation Research (30 credits).
4. Other. Additional coursework, Independent Study, RBE 598 Directed Research or RBE 699 Dissertation Research (18 credits).

Doctoral Qualifiers

The Doctoral Qualifiers evaluate each student's level of academic preparation. The Doctoral Qualifiers consist of four topic qualifiers: Technical, Writing, Speaking, and Research. The requirements for each qualifier are described in the Graduate Regulations on the RBE website http://www.wpi.edu/academics/robotics/graddegree-phd.html. Doctoral students must successfully complete the Doctoral Qualifiers before 1) completing 30 credits towards the Ph.D. for students entering with M.S., or 60 credits towards the Ph.D. for students entering with B.S., and 2) before completing 18 credits of directed research. Advancement of the student into Ph.D. candidacy is contingent upon successful completion of the Doctoral Qualifiers.

Dissertation

Dissertation Committee

Within one semester after the successful completion of the Doctoral Qualifiers, the student, in consultation with the Research Advisor, assembles a Dissertation Committee. The committee consists of the Research Advisor and three additional members, at least one of whom must be from outside the WPI RBE Program. The Dissertation Committee is responsible for approving the Dissertation Proposal and the Dissertation.

Dissertation Proposal

The Dissertation Proposal describes the student's proposed research. The Dissertation Proposal should be sufficiently detailed to convince the Dissertation Committee of the student's understanding of the problem domain along with the significance of the proposed work.

The Dissertation Proposal must be defended in a public presentation, immediately followed by private questioning from the Dissertation Committee. The Dissertation Committee then determines the outcome of the Proposal Defense. It may accept the proposal, reject the proposal and recommend pursuit of a different topic, or require the student do additional work before reconsidering the proposal. The time frame for the student to do additional work on the Dissertation Proposal is determined by the Dissertation Committee.

Dissertation

All Ph.D. students must complete and orally defend a Dissertation prepared under the supervision of the Research Advisor. The research described in the Dissertation must be original and constitute a contribution to knowledge in the major field of the candidate. The Dissertation must be defended in a public presentation, immediately followed by private questioning from the Dissertation Committee. The Dissertation Committee then determines the outcome of the Dissertation Defense, certifying the quality and originality of the research, and the satisfactory execution of the Dissertation. It may accept the Dissertation with or without revisions, reject the Dissertation, or require the student do additional work before reconsidering the Dissertation. The time frame for the student to complete additional work is determined by the Dissertation Committee.

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Faculty

This is a joint program administered by the Computer Science, Electrical & Computer Engineering, and Mechanical Engineering departments, comprising faculty members who are interested in robotics graduate education and research and who hold advanced degrees. The Robotics Engineering undergraduate and graduate programs share the Director and Associate Directors.

B.S./M.S. in Robotics Engineering

WPI allows the double counting of up to 12 credits for students pursuing a 5-year Bachelors-Masters program. This 12 credit overlap can be achieved through the following mechanisms:

- Up to 12 graduate credits in RBE, CS, ECE, or ME taken by the student may be counted towards meeting the engineering/science/elective requirements of the student's undergraduate major, subject to approval by his/her major department.
- Up to 4 credits (2/3 undergraduate units) of 4000-level undergraduate courses taken by the student in his/her undergraduate major program may be counted towards the requirements of the Masters Degree in Robotics Engineering if they can be placed in one of the requirement categories listed above and are approved by the Robotics Engineering Graduate Program Committee.
- Up to 3 credits (1/2 undergraduate unit) can be earned towards fulfillment of the thesis requirement by double counting a Major Qualifying Project, provided that:
  - the MQP involves substantial use of Robotics Engineering at an advanced level,
  - the thesis research is a continuation or extension of the MQP work,
  - the student satisfies the thesis requirement by completing at least 6 additional credits of RBE 599 Thesis Research, and
  - the thesis advisor and Robotics Engineering Graduate Program Committee approve the double counting.

MQP work may not be double-counted toward the non-thesis option.

Summary of Credit Requirements

		Non-Thesis		Thesis	
		M.S. Only	B.S./M.S.	M.S. Only	B.S./M.S.
Robotics Core	Foundations	9	9	9	9
	Other Core	6	6	6	6
Engineering Context		3	3	3	3
Electives		9	9	3	3
Thesis		—	—	9	MQP+6
Capstone Course/Research/Practicum		3	3	—	—
Double Counted Courses		—	(12)	—	(9)
Total		30	18	30	18

Course Descriptions

All courses are 3 credits unless otherwise noted.

RBE 500. Foundations of Robotics

Mathematical foundations and principles of processing sensor information in robotic systems. Topics include an introduction to probabilistic concepts related to sensors, sensor signal processing, multi-sensor control systems and optimal estimation. The material presented will focus on the types of control problems encountered when a robot must operate in an environment where sensor noise and/or tracking errors are significant. Techniques for assessing the stability, controllability and expected accuracy of multi-sensor control and tracking systems will be presented. Lab projects will involve processing live and synthetic data, robot simulation, and projects involving the control of robot platforms. (Prerequisites: Differential Equations (MA 2051 or equivalent), Linear Algebra (MA 2071 or equivalent) and the ability to program in a high-level language.)

RBE/ME 501. Robot Dynamics

Foundations and principles of robotic manipulation. Topics include computational models of objects and motion, the mechanics of robotic manipulators, the structure of manipulator control systems, planning and programming of robot actions. The focus of this class is on the kinematics and programming of robotic mechanisms. Important topics also include the dynamics, control, sensor and effector design, and automatic planning methods for robots. The fundamental techniques apply to arms, mobile robots, active sensor platforms, and all other computer-controlled kinematic linkages. The primary applications include robotic arms and mobile robots and lab projects would involve programming of representative robots. An end of term team project would allow students to program robots to participate in challenges or competitions. (Prerequisite: RBE 500 or equivalent.)

RBE 502. Robot Control

This course demonstrates the synergy between the control theory and robotics through applications and provides an in-depth coverage of control of manipulators and mobile robots. Topics may include kinematic and dynamic models, trajectory and motion planning, feedback control, compliance and force control, impedance control, control of redundant manipulators, control of underactuated robots, adaptive robot control, integrated force and motion control, digital implementation of control laws, model identification and parameter estimation techniques. Course projects will emphasize modeling, simulation and practical implementation of control systems for robotic applications. (Prerequisites: Linear algebra; Differential equations; Linear systems and control theory as in ECE 504 or consent of the instructor.)

RBE 510/ME 5204. Multi-Robot Systems

(2 credits)

This course covers the foundation and principles of multi-robot systems. The course will cover the development of the field and provide an overview on different control architectures (deliberative, reactive, behavior-based and hybrid control), control topologies, and system configurations (cellular automata, modular robotic systems, mobile sensor networks, swarms, heterogeneous systems). Topics may include, but are not limited to, multi-robot control and connectivity, path planning and localization, sensor fusion and robot informatics, task-level control, and robot software system design and implementation. These topics will be pursued through independent reading, class discussion, and a course project. The course will culminate in a group project focusing on a collaborative/cooperative multi-robot system. The project may be completed through simulation or hands-on experience with available robotic platforms. Groups will present their work and complete two professional-quality papers in IEEE format. (Prerequisites: Linear algebra, differential equations, linear systems, controls, and mature programming skills, or consent of the instructor.) Students cannot receive credit for this course if they have taken the Special Topics (ME 593S) version of the same course.

RBE 520. Biomechanics and Robotics

This course introduces Biomechanics and Robotics as a unified subject addressing living and man-made "organisms". It draws deep connections between the natural and the synthetic, showing how the same principles apply to both, starting from sensing, through control, to actuation. Those principles are illustrated in several domains, including locomotion, prosthetics, and medicine. The following topics are addressed: Biological and Artificial sensors, actuators and control, Orthotics Biomechanics and Robotics, Prosthetic Biomechanics and Robotics: Artificial Organs and Limbs, Rehabilitation Robotics and Biomechanics: Therapy, Assistance and Clinical Evaluation, Human-Robot Interaction and Robot Aided Living for Healthier Tomorrow, Sports, Exercise and Games: Biomechanics and Robotics, Robot-aided Surgery, Biologically Inspired Robotics and Micro- (bio)robotics, New Technologies and Methodologies in Medical Robotics and Biomechanics, Neural Control of Movement and Robotics Applications, Applied Musculoskeletal Models and Human Movement Analysis. This course meshes physics, biology, medicine and engineering and introduce students to subject that holds a promise to be one of the most influential innovative research directions defining the 21st century. (Recommended background: foundation of physics, linear algebra and differential equations; basic programming skills e.g. using MATLAB, undergraduate level biomechanics, robotics);

RBE 526/CS 526. Human-Robot Interaction

This course focuses on human-robot interaction and social robot learning, exploring the leading research, design principles and technical challenges we face in developing robots capable of operating in real-world human environments. The course will cover a range of multidisciplinary topics, including physical embodiment, mixed-initiative interaction, multi-modal interfaces, human-robot teamwork, learning algorithms, aspects of social cognition, and long-term interaction. These topics will be pursued through independent reading, class discussion, and a final project. (Prerequisites: Mature programming skills and at least undergraduate level knowledge of Artificial Intelligence, such as CS 4341. No hardware experience is required.)

RBE 540. Sensitive Robotics

This course introduces an approach to robotics called Sensitive Robotics. This approach allows robots to perform complex tasks by using large array of sensors that provide information relevant to the task at hand. The course studies the hardware and software implications of this approach. At the hardware level, we discuss the mechanical and electrical characteristic of the sensors and actuators, the design consideration of arms and limbs, and the hardware architecture alternatives. At the software level, we discuss the implications that the hardware changes have in the software architecture, and the control algorithms. Machine learning techniques, needed to deal with large array of sensors, are also covered. The case of robotic manipulation (sensitive manipulation) is introduced as an example of this approach and it is expanded to walking, flying and swimming robots. (Prerequisites: RBE 500)

RBE 548. Model-Based Design

This course addresses the what (modeling), how (design) and why (analysis) of systems through the use of model-based design process. System models will be essential to four key aspects of the design process, derivation of executable specifications, hardware and software design based on simulations, implementation by code generation, and continuous testing and verification. Model-based design can be an effective tool to ensure safe, efficient and reliable operation of cyber-physical systems in which computation and communication are tightly integrated with physical processes. Topics may include modeling continuous and discrete dynamics, heterogeneous models, hybrid systems, stochastic models, models of computation, analysis and design of embedded control systems with applications in robotics, system simulation, validation and verification techniques, time-critical systems and human-in-the-loop cyber-physical systems. The examples throughout the course will be drawn from practical robot applications as robotics requires a whole system design approach at the cross-section of environmental models, physical components and algorithms. Course projects will emphasize model-based design for control of robotic systems and smart environments. Students who are not RBE majors will be encouraged to undertake projects that reflect their own engineering systems interests consistent with the specific project objectives. (Prerequisites: linear algebra and differential equations; embedded systems; linear systems and control theory or consent of the instructor.)

RBE/CS 549. Computer Vision

This course examines current issues in the computer implementation of visual perception. Topics include image formation, edge detection, segmentation, shape-from-shading, motion, stereo, texture analysis, pattern classification and object recognition. We will discuss various representations for visual information, including sketches and intrinsic images. (Prerequisites: CS 534, CS 543, CS 545, or the equivalent of one of these courses.)

RBE 550. Motion Planning

Motion planning is the study of algorithms that reason about the movement of physical or virtual entities. These algorithms can be used to generate sequences of motions for many kinds of robots, robot teams, animated characters, and even molecules. This course will cover the major topics of motion planning including (but not limited to) planning for manipulation with robot arms and hands, mobile robot path planning with non-holonomic constraints, multi-robot path planning, high-dimensional sampling-based planning, and planning on constraint manifolds. Students will implement motion planning algorithms in open-source frameworks, read recent literature in the field, and complete a project that draws on the course material. The PR2 robot will be available as a platform for class projects. Physical robot platforms will be available for class projects. Prerequisites: Undergraduate Linear Algebra, experience with 3D geometry, and significant programming experience.

RBE 580/ME 5205. Biomedical Robotics (2 credits)

This course will provide an overview of a multitude of biomedical applications of robotics. Applications covered include: image-guided surgery, percutaneous therapy, localization, robot-assisted surgery, simulation and augmented reality, laboratory and operating room automation, robotic rehabilitation, and socially assistive robots. Specific subject matter includes: medical imaging, coordinate systems and representations in 3D space, robot kinematics and control, validation, haptics, teleoperation, registration, calibration, image processing, tracking, and human-robot interaction.Topics will be discussed in lecture format followed by interactive discussion of related literature. The course will culminate in a team project covering one or more of the primary course focus areas. (Prerequisites: Linear algebra, ME/RBE 501 or equivalent.) Students cannot receive credit for this course if they have taken the Special Topics (ME 593U) version of the same course.

RBE 594. Capstone Project Experience in Robotics Engineering

This project-based course integrates robotics engineering theory and practice, and provides the opportunity to apply the skills and knowledge acquired in the Robotics Engineering curriculum. The project is normally conducted in teams of two to four students. Students are encouraged to select projects with practical significance to their current and future professional responsibilities. The projects are administered, advised, and evaluated by WPI faculty as part of the learning experience, but students are also encouraged to seek mentorship from experienced colleagues in the Robotics Engineering profession. (Prerequisites: Since the Capstone Project will draw on knowledge obtained throughout the degree program, it is expected that students will have completed most or all of the coursework within their plan of study before undertaking the capstone project.)

RBE 595. Special Topics

Arranged by individual faculty with special expertise, these courses survey fundamentals in areas that are not covered by the regular Robotics Engineering course offerings. Exact course descriptions are disseminated by the Robotics Engineering Program well in advance of the offering. (Prerequisite: Consent of instructor.

RBE 596. Robotics Engineering Practicum

This practicum provides an opportunity to put into practice the principles studied in previous courses. It will generally be conducted off campus and will involve real-world robotics engineering. Overall conduct of the practicum will be supervised by a WPI RBE faculty member; an on-site liaison will direct day-to-day activity. For a student from industry, an internship may be sponsored by his or her employer. The project must include substantial analysis and/or design related to Robotics Engineering and will conclude with a substantial written report. A public oral presentation must also be made, to both the host organization and a committee consisting of the supervising faculty member, the on-site liaison and one additional WPI faculty member. This committee will verify successful completion of the internship. (Prerequisite: Consent of practicum faculty advisor.)

RBE 597. Independent Study

Approved study of a special subject or topics selected by the student to meet his or her particular requirements or interests. (Prerequisite: B.S. in CS, ECE, ME, RBE or equivalent and consent of advisor.)

RBE 598. Directed Research

For M.S. or Ph.D. students wishing to gain research experience peripheral to their thesis topic, M.S. students undertaking a capstone design project, or doctoral students wishing to obtain research credit prior to admission to candidacy. (Prerequisite: Consent of research advisor.)

RBE 599. Thesis Research

For master's students wishing to obtain research credit toward the thesis. (Prerequisite: Consent of thesis advisor.)

RBE 699. Dissertation Research

For Ph.D. students wishing to obtain a research credit towards the dissertation. Prerequisite: Consent of research advisor.

Social Science & Policy Studies

Faculty

O. V. Pavlov, Associate Professor; Ph.D., University of Southern California, 2000. Economics of information systems, political economy, system dynamics, computational economics, complex economic dynamics; opavlov@wpi.edu.

M. J. Radzicki, Associate Professor; Ph.D., University of Notre Dame du Lac, 1985. Economic growth, environmental and energy policy, fiscal and monetary policy, combining post keynesian economics and institutional economics with system dynamics; mjradz@wpi.edu

K. Saeed, Professor; Ph.D., Massachusetts Institute of Technology, 1981. Sustainable economic development, system dynamics; organizational development, political economy; health care delivery; saeed@wpi.edu

Adjunct Faculty

K. Chichakly, Ph.D., University of Vermont. Lead Programmer, ISEE Systems

R. Eberlein, Ph.D., Massachusetts Institute of Technology. Consultant, Astutesd

A. Ford, Professor; Ph.D., Washington State University. Regional planning

J. M. Lyneis, Ph.D., University of Michigan, 1974. System dynamics, project dynamics and management, economic dynamics, market and industry behavior, (de)regulation, forecasting, business strategy; jmlyneis@wpi.edu

J. Morecroft, Ph.D., Massachusetts Institute of Technology, 1979. Senior Fellow, Management Science and Operations, London Business School

K. Warren, Ph.D., London Business School, 1995. Chairman, Global Strategy Dynamics

Program of Study

The System Dynamics Program offers a graduate certificate in System Dynamics, a master of science in System Dynamics, and an interdisciplinary master of science in systems modeling. Individuals may also utilize WPI's interdisciplinary Ph.D. program to create a unique doctoral program incorporating system dynamics research. Through these programs, graduate students create and learn from their own models in a variety of research areas.

Systems Thinking Certificate

This certificate program is designed to meet the needs of a variety of corporations and individuals who are interested in systems engineering education but who may have undergraduate degrees in non-engineering disciplines. The Program of Study shown below presents the requirements for the certificate. Inherent in this program of study is sufficient course selection flexibility for students to, if desired and admitted, be able to continue their graduate studies and earn an M.S. degree in Systems Engineering or SSPS/System Dynamics, depending on student interest and background. For more information, consult the WPI website.

Graduate Certificate Program in System Dynamics

System dynamics is a computer simulation-based approach to the construction and analysis of mathematical models of economic, social, and physical systems. System dynamics modeling is applied in a variety of application areas such as biology, ecology, economics, business, public policy, etc. There is a strong and growing demand for graduate-level training in systems modeling in industry and government organizations. To meet this need WPI has developed a program of several on-line graduate classes in system dynamics.

Requirements

The Graduate Certificate in System Dynamics consists of 15 credit hours of graduate study (5 courses). Students take one or both of our Foundation Courses (SD550 and SD551) depending on their experience, and fill out the remainder of their program with a variety of elective choices in system dynamics covering methodological topics and application areas. Students must work with a faculty advisor to delineate a Plan of Study for their certificate program. To be counted towards the certificate, the plan must be developed no later than the completion of the second course. Further details about the certificate requirements are available at https://www.wpi.edu/academics/online/study/system-dynamics-certificate

Admission

Students will be eligible for admission into the graduate certificate program if they have earned an undergraduate degree from an accredited university consistent with the WPI Graduate Catalog. Students should have a bachelor's degree in science or engineering. Students with other backgrounds will be considered based on their interest, formal education, and work experience. Admission decisions will be made by the System Dynamic graduate program committee based on all factors presented in the application, including prior academic performance, quality of professional experience, letters of recommendation, etc.

Master of Science in System Dynamics

The Masters Degree program in System Dynamics prepares students for the professional practice of system dynamics computer simulation modeling, which includes an understanding of the endogenous feedback relationships that cause observed patterns of behavior in socio-technical-economic systems, and knowledge of the use of simulation modeling for experimental analysis aimed at solving a variety of problems in the private and public policy domains. This training will enable students to look across disciplinary boundaries to discern the impacts of well-intentioned policies and technological solutions holistically. It will also prepare students to understand the policy implementation

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process in various organizational settings and create confidence in the success of policy interventions. Many companies are currently supporting the training of their middle level managers in systems thinking and system dynamics because they regard it as essential for senior management roles in industry and the public sector. The WPI Masters in System Dynamics will offer an enhanced level of training for such roles. Combined with an undergraduate degree in engineering, the life sciences, the humanities, or social science, a Masters Degree in System Dynamics will enable a decision maker to more fully understand cross-disciplinary issues, thus making him or her an innovative contributor to their respective work settings. The WPI Masters Degree in System Dynamics may be pursued on-line. For more information, go to https://www.wpi.edu/academics/online/study/system-dynamics-ms.

Degree Requirements

The. M.S. degree in system dynamics consists of 30 credit hours of course work (10 courses). At least 21 of these credits must be in system dynamics. Courses are selected from three bins: foundation courses (6 credits), methodological courses (9-12 credits), and application courses (6-9 credits). The remaining 9 credits may be additional system dynamics courses or may be taken from a list of approved courses in mathematics, organizational behavior, finance, and public planning. Up to 6 credit hours my be completed as supervised project work. All entering students must submit a plan of study identifying courses to be taken before the end of the first semester in the program. The plan of study must be approved by the faculty advisor. Further details about the M.S. requirements are available at https://www.wpi.edu/academics/online/study/system-dynamics-ms.

Admission

Students will be eligible for admission to the program if they have earned an undergraduate degree from an accredited university consistent with the WPI graduate catalog. Admission will also be open to qualified WPI students who opt for a five-year Bachelors-Masters Degree, with the undergraduate major based on a student's interests. Admission decisions will be made by the System Dynamics graduate program committee based on all of the factors presented in the application.

B.S./M.S. in System Dynamics

The requirements for the proposed Masters degree in System Dynamics are structured so that undergraduate students would be able to pursue a five year Bachelors/Masters degree, in which the Bachelors degree is awarded in any major offered at WPI and the Masters degree is awarded in System Dynamics.

WPI allows the double counting of up to 12 credits for students pursuing a 5-year Bachelors-Masters Degree program. This overlap can be achieved through the following mechanisms:

- Credits from up to two system dynamics graduate courses taken by the student may be counted towards meeting the social science requirement of the student's undergraduate major.
- Credits from up to four graduate courses taken by the student may be counted towards meeting the mathematics/engineering/science/elective requirements of the student's undergraduate major, subject to approval by his/her major department.
- Credits from up to two 4000 level undergraduate courses taken by the student in his/her undergraduate major program may be counted towards the requirements of the Masters Degree in System Dynamics if they can be placed in one of the requirement categories listed above and approved by the System Dynamics Program Director.
- Up to three credits can be earned by double counting a junior and/or senior undergraduate project if it involves substantial use of system dynamics at an advanced level, subject to approval by the System Dynamics graduate program committee.

Interdisciplinary Master's Degree in Systems Modeling

There is a strong and growing demand for graduate-level training in systems modeling. Interest in system dynamics and formal mathematical modeling in industry and government organizations increases every year. Many employees of these organizations, and those seeking career changes, desire to improve their skills in these methodologies. In addition, these modeling methods are growing as a research tool and many prospective Ph.D. students desire to build skills in them.

Systems modeling subsumes both formal and computer simulation-based approaches to the construction and analysis of mathematical models of economic, social, and physical systems. It builds on methodologies such as feedback control theory, optimization, numerical methods and computer simulation. Moreover, systems modeling is applied in a variety of application areas such as management, biology, ecology, economics, etc. Students of systems modeling study not only the basic courses in System Dynamics, but also explore its methodological underpinnings in other disciplines and apply the methods to other disciplines, preparing them to mobilize the modeling concepts they learn to problem solving in the real world.

To meet this need, the departments of Mathematical Sciences and Social Science & Policy Studies have established an interdisciplinary master's degree in systems modeling. This interdisciplinary 30 credit-hour program utilizing courses taught in Mathematical Sciences, System Dynamics, and electives taught in engineering, science and management departments.

Admission

Students should have a bachelor's degree in science or engineering. Students with other backgrounds will be considered based on their interest, formal education, and work experience. Many students pursuing a 5-year bachelors/masters program also enroll for a masters in systems modeling along with a bachelors in a major of their choice to prepare for meeting the challenges of their future careers.

Degree Requirements

Students must complete 30 credit hours of coursework: 15 credit hours in system dynamics and 15 credit hours in mathematical modeling and an applications area (e.g. industrial engineering, management, infrastructure planning, telecommunications planning, power systems). Up to 6 of these latter credit hours may be done as supervised project work. New students must submit a Plan of Study identifying the courses to be taken and a prospective project topic before the end of the first semester in the program. If the student has earned a Graduate Certificate in System Dynamics from WPI, the Plan of Study must be submitted with the application materials. The Plan of Study must be approved by the administering faculty who will serve as advisors.

System Dynamics Interdisciplinary Ph.D.

The Social Science and Policy Studies Department offers a PhD program in system dynamic in which the students are encouraged to pursue interdisciplinary research applying system dynamics modeling and computer simulation to diverse problems. The program lets you develop your individually tailored plan of study with highly regarded faculty and other advisors across disciplines. The rigorous plan includes high-level system dynamics classes and courses in your area of application, passing qualifying exams, dissertation proposal and final defense of dissertation. Diverse, online coursework helps students discover solutions for complex business and public policy problems. On-campus research offers a multidisciplinary perspective as you work with expert and practicing faculty to form a committee and develop a plan of study.

Admission

Admission criteria for the doctoral program are outlined on page 11. Applicants to the SSPS interdisciplinary doctoral program must have prior B.S. and M.S. degrees. A GRE is required, but can be waived in special cases with consent of the sponsoring group.

The Doctoral Committee and Plan of Study

Each program of study is tailored to the interests of the student and the interests of the participating faculty members. The first step in establishing a program is the selection of a doctoral program committee of no less than three faculty members, with at least one faculty member from each participating department.

A Plan of Study, of at least 60 credit hours, is then developed with the help of the student's doctoral program committee to meet the degree requirements and the interests of the student and the participating faculty. Minimum and typical requirements for the Plan of Study are discussed below.

Requirements for the Interdisciplinary System Dynamics Doctorate at WPI

In addition to meeting the general requirements of the doctoral degree at WPI, students in the interdisciplinary System Dynamics doctoral program must also take a qualifying examination prior to earning 18 credit hours of work.

There are four stages toward an interdisciplinary doctorate involving System Dynamics: first, submitting an approved Plan of Study to the Registrar; second, passing a qualifying examination; third, defending a dissertation proposal and becoming a doctoral candidate; and fourth, defending the dissertation. The requirements stated below apply to students already having a master's degree and are focused on 60 credits of graduate work beyond the M.S. degree.

Summary of Post-Master's Degree Credits

Graduate coursework
Credits: 18 max
Pre-qualifying exam coursework

Graduate coursework
Credits: 6 min
Post-qualifying exam coursework

Dissertation
Credits: 18 max
Post-qualifying exam, pre-candidacy exam dissertation credits

Dissertation
Credits: 12 min
Post-candidacy exam dissertation credits to make at least 30 dissertation credits totally

Graduate coursework or dissertation credits
Credits: Balance
Post-candidacy exam credits to make at least 60 total credits

Total Post-M.S. Credits: 60

For more information, go to https://www.wpi.edu/academics/study/system-dynamics-phd.

Course Descriptions

All courses are 3 credits unless otherwise noted.

SD 550. System Dynamics Foundation: Managing Complexity

Why do some businesses grow while others stagnate or decline? What causes oscillation and amplification – the so called "bullwhip" – in supply chains? Why do large scale projects so commonly over overrun their budgets and schedules? This course explores the counter-intuitive dynamics of complex organizations and how managers can make the difference between success and failure. Students learn how even small changes in organizational structure can produce dramatic changes in organizational behavior. Real cases and computer simulation modeling combine for an in-depth examination of the feedback concept in complex systems. Topics include: supply chain dynamics, project dynamics, commodity cycles, new product diffusion, and business growth and decline. The emphasis throughout is on the unifying concepts of system dynamics.

SD 551. Modeling and Experimental Analysis of Complex Problems

This course deals with the hands on detail related to analysis of complex problems and design of policy for change through building models and experimenting with them. Topics covered include: slicing complex problems and constructing reference modes; going from a dynamic hypothesis to a formal model and organization of complex models; specification of parameters and graphical functions; experimentations for model understanding, confidence building, policy design and policy implementation. Modeling examples will draw largely from public policy agendas. (Prerequisites: SD 550 System Dynamics Foundation: Managing Complexity.)

SD 552. System Dynamics for Insight

The objective of this course is to help students appreciate and master system dynamics' unique way of using of computer simulation models. The course provides tools and approaches for building and learning from models. The course covers the use of molecules of system dynamics structure to increase model building speed and reliability. In addition, the course covers recently developed eigenvalue-based techniques for analyzing models as well as more traditional approaches. (Prerequisites: SD 550 System Dynamics Foundation: Managing Complexity and SD 551 Modeling and Experimental Analysis of Complex Problems.)

SD 553. Model Analysis and Evaluation Techniques

This course focuses on analysis of models rather than conceptualization and model development. It provides techniques for exercising models, improving their quality and gaining added insights into what models have to say about a problem. Five major topics are covered: use of subscripts, achieving and testing for robustness, use of numerical data, sensitivity analysis, and optimization/calibration of models. The subscripts

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discussion provides techniques for dealing with detail complexity by changing model equations but not adding additional feedback structure. Robust models are achieved by using good individual equation formulations and making sure that they work together well though automated behavioral experiments. Data, especially time series data, are fundamental to finding and fixing shortcomings in model formulations. Sensitivity simulations expose the full range of behavior that a model can exhibit. Finally, the biggest section, dealing with optimization and calibration of models develops techniques for both testing models against data and developing policies to achieve specified goals. Though a number of statistical issues are touched upon during the course, only a basic knowledge of statistics and statistical hypothesis testing is required. (Prerequisites: SD 550 System Dynamics Foundation: Managing Complexity and SD 551 Modeling and Experimental Analysis of Complex Problems, or permission of the instructor.)

SD 554. Real World System Dynamics

In this course students tackle real-world issues working with real managers on their most pressing concerns. Many students choose to work on issues in their own organizations. Other students have select from a number of proposals put forward by managers from a variety of companies seeking a system dynamics approach to important issues. Students experience the joys (and frustrations) of helping people figure out how to better manage their organizations via system dynamics. Accordingly the course covers two important areas: consulting (i.e. helping managers) and the system dynamics standard method - a sequence of steps leading from a fuzzy "issue area" through increasing clarity and ultimately to solution recommendations. The course provides clear project pacing and lots of support from the instructors and fellow students. It is recommend that students take SD 552 Real World System Dynamics toward the end of their system dynamics coursework as it provides a natural transition from coursework to system dynamics practice. (Prerequisites: SD 550 System Dynamics Foundation: Managing Complexity and SD 551 Modeling and Experimental Analysis of Complex Problems.)

SD 556. Strategic Modeling and Business Dynamics

The performance of firms and industries over time rarely unfolds in the way management teams expect or intend. The purpose of strategic modeling and business dynamics is to investigate dynamic complexity by better understanding how the parts of an enterprise operate, fit together and interact. By modeling and simulating the relationships among the parts we can anticipate potential problems, avoid strategic pitfalls and take steps to improve performance. We study a variety of business applications covering topics such as cyclicality in manufacturing, market growth and capital investment. The models are deliberately small and concise so their structure and formulations can be presented in full and used to illustrate principles of model conceptualization, equation formulation and simulation analysis. We also review some larger models that arose from real-world applications including airlines, the oil industry, the chemicals industry and fast moving consumer goods. Students work with selected business policy problems based on generic structures discussed in the lessons. (Prerequisite: SD 550 System Dynamics Foundation: Managing Complexity)

SD 557. Latent Structures, Unintended Consequences, and Policy

This course addresses policy resilience and unintended consequences arising out of actions that are not cognizant of the latent structure causing the problem. An attempt is made to identify the generic systems describing such latent structures. The latent structures discussed include a selection from capacity constraining and capacity enabling systems, resource allocation, and economic cycles of various periodicities. Problems discussed in lessons include pests, gang violence, terrorism, political instability, professional competence in organizations, urban decay, and economic growth and recessions. Students work with selected public policy problems relevant to the generic latent structures discussed in the course. (Prerequisites: SD 550 System Dynamics Foundation: Managing Complexity, SD 551 Modeling and Experimental Analysis of Complex Problems)

SD 558. Introduction to Agent-Based Modeling

The purpose of this course is to provide students with an introduction to the field of agent-based computer simulation modeling in the social sciences. The course begins with an outline of the history of the field, as well as of the similarities and differences between agent-based computer simulation modeling and system dynamics computer simulation modeling. An important goal of the course is to provide students with guidelines for deciding when it is preferable to apply agent-based modeling, and when it is preferable to apply system dynamics modeling, to a particular problem. Through a series of example models and homework exercises students are introduced to the software that is used in the course. Generally speaking, as the course progresses students will be introduced to increasingly complicated agent-based models and exercises so that their modeling skills will grow. The goal is to increase students' modeling skills so that they will eventually be able to create their own agent-based models from scratch. The remainder of the course is devoted to examining models of socioeconomic phenomena that reside within two broad categories of agent-based models: cellular automata models and multi-agent models. Along the way the cross-category, cross-disciplinary, principles of agent-based modeling (micro-level agents following simple rules leading to macro-level complexity, adaptation, evolving structure, emergence, non-ergodicity) are emphasized.

SD 560. Strategy Dynamics

This course provides a rigorous set of frameworks for designing a practical path to improve performance, both in business and non-commercial organizations. The method builds on existing strategy concepts, but moves substantially beyond them, by using the system dynamics method to understand and direct performance through time. Topics covered include: strategy, performance and resources; resources and accumulation; the 'Strategic Architecture'; resource development; rivalry and the dynamics of competition; strategy, policy and information feedback; resource attributes; intangible resources; strategy, capabilities and organization; industry dynamics and scenarios. Case studies and models are assigned to students for analysis.

SD 561. Energy and Environmental Dynamics

This course helps students develop understanding and proficiency in system dynamics simulation of energy and environmental problems. The majority of the content is devoted to case studies that focus on energy, water and environmental problems. Major business applications deal with boom and bust in power plant construction and a similar pattern of boom and bust in real-estate construction. The text used is: Ford, Andrew. 2009. *Modeling the Environment, 2nd Edition.* Island Press. The book's website (http://www.wsu.edu/~forda/AA2nd.html) provides model files, background on the case studies and a wide variety of extra exercises. For example, Students interested in water resource management can simulate the complex tradeoffs in the management of large river basins; students interested in water quality can experiment with models of accelerated eutrophication of fresh water lakes. A highlight of SD 561 is a class project. One option is to select one of the more challenging sets of exercises from the book (or the book's website). Such a project is often the best way to conclude SD561 for students who are new to system dynamics. The other option is to improve one of the models from the book or the website. This option is usually best for students with previous course work in system dynamics. Their project report will explain why their simulations are an improvement on the published simulations. And they will explain whether the conclusions from their modeling reinforce or contradict the conclusions from the book. (Prerequisite: SD 550 or permission of the instructor).

SD 562. Project Dynamics

This course will introduce students to the fundamental dynamics that drive project performance, including the rework cycle, feedback effects, and inter-phase "knock-on" effects. Topics covered include dynamic project problems and their causes: the rework cycle and feedback effects, knock-on effects between project phases; modeling the dynamics: feedback effects, schedule pressure and staffing, schedule changes, inter-phase dependencies and precedence; strategic project management: project planning, project preparation, risk management, project adaptation and execution cross project learning; multi-project issues. A simple project model will be created, and used in assignments to illustrate the principles of "strategic project management." Case examples of different applications will be discussed. (Prerequisite: SD 550 System Dynamics Foundation: Managing Complexity.)

SD 565. Macroeconomic Dynamics

There are three parts to this course. The first acquaints a student with dynamic macroeconomic data and the stylized facts seen in most macroeconomic systems. Characteristics of the data related to economic growth, economic cycles, and the interactions between economic growth and economic cycles that are seen as particularly important when viewed through the lens of system dynamics will be emphasized. The second acquaints a student with the basics of macroeconomic growth and business cycle theory. This is accomplished by presenting well-known models of economic growth and instability, from both the orthodox and heterodox perspectives, via system dynamics. The third part attempts to enhance a student's ability to build and critique dynamic macroeconomic models by addressing such topics as the translation of difference and differential equation models into their equivalent system dynamics representation, fitting system dynamics models to macroeconomic data, and evaluating (formally and informally) a model's validity for the purpose of theory selection. (Prerequisites: SD 550 System Dynamics Foundation: Managing Complexity.)

SS 590. Special Topics in Social Science and Policy Studies

(credits: 1-4)

Individual or group studies on any topic relating to social science and policy studies selected by the student and approved by the faculty member who supervises the work. (Prerequisites: permission of the instructor.

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STEM for Educators

Faculty

Learning Sciences and Technologies

N. T. Heffernan, Professor and Director; Ph.D., Carnegie Mellon University. Intelligent tutoring agents, artificial intelligence, cognitive modeling, machine learning.

I. Arroyo, Assistant Professor; Ed.D., M.S., University of Massachusetts, Amherst. Learning with novel technologies; multimedia learning; intelligent tutoring systems; wearable learning and e-Textiles; learner characteristics and their relationship to learning; connection between affect and learning; educational data mining and student modeling.

J. E. Beck, Associate Professor; Ph.D., University of Massachusetts, Amherst. Machine learning, educational data mining, intelligent tutoring systems, human learning and problem solving.

E. Ottmar, Assistant Professor; Ph.D., University of Virginia. Mathematics teaching and learning; mathematics development and cognition; interventions in schools; instructional quality; social and emotional learning; motivation and engagement; perceptual learning; teacher/child interactions; observational measurement development.

Mathematics:

J. Goulet, Teaching Professor and Coordinator, Master of Mathematics for Educators Program; Ph.D., Rensselaer Polytechnic Institute, 1976. Applications of linear algebra, cross departmental course development, project development, K-12 relations with colleges, mathematics of digital and analog sound and music.

M. Johnson, Teaching Assistant Professor; Ph.D., Clark University 2012. Industrial organization, game theory, graph theory and probability.

B. Servatius, Professor; Ph.D., Syracuse University, 1987. Combinatorics, matroid and graph theory, structural topology, geometry, history and philosophy of mathematics.

Physics

I. Stroe, Assistant Teaching Professor and Director of Master of Science in Physics for Educators; Ph.D., Clark University. Experimental biophysics, protein structure, dynamics and functionality.

G. S. Iannacchione, Professor; Ph.D., Kent State University. Soft condensed matter physics/complex fluids, liquid-crystals, calorimetry, and order-disorder phenomena.

F. Dick, Associate Teaching Professor; Ph.D., Worcester Polytechnic Institute. Nuclear and particle physics, astrophysics and planetary.

Questions

Contact Katie Elmes, Senior Program Coordinator; kaelmes@wpi.edu; 508-831-5703.

Program of Study

Majors in the STEM for Educators program are designed specifically for middle school, high school and community college in-service educators. The majors emphasize coursework in the content area (math or physics) along with classes in core assessment and evaluation theory, and a participant-designed project. Educators will find that this combination of coursework held during afternoon and evening times will both fit their needs as busy professionals and broaden knowledge and skills that will support what they do in their classrooms. The program may satisfy Massachusetts Professional Licensure requirements for middle and high school educators.

Master of Science in Mathematics for Educators (MMED)

This degree blends together an emphasis on courses in mathematics content with core assessment and evaluation theory courses and a participant-designed project. The math content courses, designed for educators, offer a solid foundation in areas such as geometry, algebra, modeling, discrete math and statistics. They additionally include the study of modern applications. Participants have the opportunity to develop materials, based on coursework, which may be used in their own classrooms. Technology is introduced whenever possible to help educators become familiar with the options available for use in classrooms. Examples of this include Geometer's Sketchpad and the TI CBL for motion and heat.

*For information about the Master of Mathematics for Educators program, please look under the Mathematical Sciences page.

Master of Science in Physics for Educators (MPED)

This degree blends together an emphasis on courses in physics content with core assessment and evaluation theory courses and a participant-designed project. The physics content courses are designed to give educators a deep but applicable understanding of physics that both make advanced physics topics easily accessible to educators and appropriate to their roles of guiding their students. The physics content is organized into three parts: Depth (e.g. Mechanics and Topics in Modern Physics), Methods (e.g. Computational and Experimental Physics Methods), and Breadth (e.g. Research Experience for Educators and Physics in Popular Culture). Support for degree candidates extends beyond the specific coursework and projects as participants will become part of a network of physicists which ranges from local individuals to a much broader community.

Admission Requirements

Candidates for any major in the STEM for Educators programs must have a Bachelor's degree, a background equivalent to at least a minor in one of the STEM areas of interest and either a teacher certification in a STEM field or a full-time teaching position in one of these disciplines. Applicants can be teaching at any grade level.

Degree Requirements

Each of the programs within STEM for Educators requires 30 credit hours of work. As part of this, participants must take 9 credits in core assessment and evaluation theory, 15 credits in the content area specific to the major, and 6 credits for the participant-designed project. All courses in these programs are based on a three-semester year where most participants take one to two classes per semester.

Course Requirements

Core Assessment and Evaluation Theory Courses

To fulfill the 9 credits in core assessment and evaluation theory, participants must take a minimum of one course from each of the three sections below. Full course descriptions are listed under the appropriate department.

(a) Learning Theory, Environments, and Cognition:
   1) SEME/PSY 501 – Foundations of the Learning Sciences (3 cr)
   2) SEME/PSY 502 – Educational Learning Environments (3 cr)
   3) SEME/PSY 504 – Meta-cognition, Motivation, and Affect (3 cr)

(b) Qualitative and Quantitative Analysis and Assessment:
   4) SEME/MME 524 – Probability, Statistics and Data Analysis I (2 cr)
   5) SEME/MME 525 – Probability, Statistics and Data Analysis II (2 cr)
   6) SEME/CS 565 – User Modeling (3 cr)
   7) SEME/CS 566 – Graphical Models for Reasoning Under Uncertainty (3 cr)
   8) SEME/CS 567 – Empirical Methods for Human-Centered Computing (3 cr)

(c) Current Education and Education Research Issues:
   9) SEME 562 – Issues in Education (3 cr)
   10) SEME/PSY 503 – Research Methods for the Learning Sciences (3 cr)
   11) SEME/CS 568 – Artificial Intelligence for Adaptive Educational Tech. (3 cr)

Math Content Courses

15 credit hours of content area courses are required. Full course descriptions are listed under mathematics.

MME 518 – Geometrical Concepts (3 cr)

MME 522 – Applications of Calculus (2 cr)

MME 523 – Analysis with Applications (2 cr)

MME/SEME 524 – Probability, Statistics and Data Analysis I (2 cr)

MME/SEME 525 – Probability, Statistics and Data Analysis II (2 cr)

MME 526 – Linear Models I (2 cr)

MME 527 – Linear Models II (2 cr)

MME 528 – Mathematical Modeling and Problem Solving (2 cr)

MME 529 – Numbers, Polynomials and Algebraic Structures (2 cr)

MME 531 – Discrete Mathematics (3 cr)

(Note that MME/SEME-524/525 are also listed under Core Assessment and Evaluation Theory. Only one of these two courses can be double counted towards the content area.)

Physics Content Courses

The physics content, a total of 15 credit hours, is satisfied with 8 credits in physics depth, 4 credits in physics methods, and 3 credits in physics breadth. Full course descriptions are listed under physics.

Depth Courses

MPE 510 – Classical Mechanics (2 cr)

MPE 520 – Electrodynamics (2 cr)

MPE 530 – Modern Physics (2 cr)

MPE 540 – Differential Equations in Nature (2 cr)

Methods Courses

MPE 550 – Computational Methods in Physics (2 cr)

MPE 560 – Experimental Methods in Physics (2 cr)

Breadth Courses

MPE 572 – Physics Research Experience for Teachers (3 cr)

MPE 574 – Physics for Citizens and Leaders (3 cr)

MPE 576 – Physics in Popular Culture (3 cr)

Culminating Project Courses

Six (6) credit hours are required. Full course descriptions are listed under mathematics.

SEME 602/MME 592 – Project Preparation/Design (2 cr)

SEME 604/MME 594 – Project Implementation (2 cr)

SEME 606/MME 596 – Project Analysis and Report (2 cr)

Course Descriptions

All courses are 3 credits unless otherwise noted.

SEME/PSY 501. Foundations of the Learning Sciences

This course covers readings that represent the foundation of the learning sciences, including: Foundations (Constructivism, Cognitive Apprenticeship, & Situated Learning); Approaches (Project-based Learning, Model-based reasoning, Cognitive Tutors); and Scaling up educational interventions. The goal of this course is for students to develop an understanding of the foundations and approaches to the Learning Sciences so that they can both critically read current literature, as well as build on it in their own research. (Prerequisites: None)

SEME/PSY 502. Educational Learning Environments

In this class, students will read and review both classic and critical current journal articles about learning technologies developed in the Learning Sciences. This course is designed to educate students on current technological approaches to curricular design, implementation, and research in the Learning Sciences. (Prerequisites: None)

SEME/PSY 503. Research Methods for the Learning Sciences

This course covers research methods used in the Learning Sciences. Students will gain expertise and understanding of think-aloud studies, cognitive task analysis, quantitative and qualitative field observations, log file analysis, psychometric, cognitive, and machine-learning based modeling, the automated administration of measures by computer, and issues of validity, reliability, and statistical inference specific to these methods. Students will learn how and when to apply a variety of methods relevant to formative, performance, and summative assessment in both laboratory and field settings. Readings will be drawn primarily from original source materials (e.g. journal articles and academic book chapters), in combination with relevant textbook chapters. (Prerequisites: SS 2400, Methods, Modeling, and Analysis in Social Science, comparable course, or instructor discretion.)

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SEME/PSY 504. Meta-cognition, Motivation, and Affect

This course covers three key types of constructs that significantly impact learning and performance in real-world settings, including but not limited to educational settings. Students will gain understanding of the main theoretical frameworks, and major empirical results, that relate individuals' meta-cognition, motivation, and affect to real-world outcomes, both in educational settings and other areas of life. Students will learn how theories and findings in these domains can be concretely used to improve instruction and performance, and complete final projects that require applying research in these areas to real-world problems. Students will do critical readings on research on this topic. (Prerequisites: None)

SEME/MME 524-25. Probability, Statistics and Data Analysis I, II

(2 credits each)

This course introduces students to probability, the mathematical description of random phenomena, and to statistics, the science of data. Students in this course will acquire the following knowledge and skills:

- Probability models-mathematical models used to describe and predict random phenomena. Students will learn several basic probability models and their uses, and will obtain experience in modeling random phenomena.
- Data analysis-the art/science of finding patterns in data and using those patterns to explain the process which produced the data. Students will be able to explore and draw conclusions about data using computational and graphical methods. The iterative nature of statistical exploration will be emphasized.
- Statistical inference and modeling-the use of data sampled from a process and the probability model of that process to draw conclusions about the process. Students will attain proficiency in selecting, fitting and criticizing models, and in drawing inference from data.
- Design of experiments and sampling studies – the proper way to design experiments and sampling studies so that statistically valid inferences can be drawn. Special attention will be given to the role of experiments and sampling studies in scientific investigation. Through lab and project work, students will obtain practical skills in designing and analyzing studies and experiments. Course topics will be motivated whenever possible by applications and reinforced by experimental and computer lab experiences. One in-depth project per semester involving design, data collection, and statistical or probabilistic analysis will serve to integrate and consolidate student skills and understanding. Students will be expected to learn and use a statistical computer package such as MINITAB.

SEME 562. Issues in Education

This course is about the theory and the practice of formative assessment. The practice will involve bringing those theories to life in the classroom. Participants will be required to actively implement the formative assessment cycle in their own teaching. Online tools that facilitate the formative assessment process will be used by the teachers. One such tool that will be required is ASSISTments. Participants will decide what data to collect evaluate and analyze. They will analyze the data in this class and with their students. They will examine their own instruction by videotaping themselves and sharing their experiences with the group. Participants will go through these steps repeatedly during the course. Participants will be required to synthesize and critique course materials through written documents and formal and informal presentations.

SEME/CS 565. User Modeling

User modeling is a cross-disciplinary research field that attempts to construct models of human behavior within a specific computer environment. Contrary to traditional artificial intelligence research, the goal is not to imitate human behavior as such, but to make the machine able to understand the expectations, goals, knowledge, information needs, and desires of a user in terms of a specific computing environment. The computer representation of this information about a user is called a user model, and systems that construct and utilize such models are called user modeling systems. A simple example of a user model would be an e-commerce site which makes use of the user's and similar users' purchasing and browsing behavior in order to better understand the user's preferences. In this class, the focus is on obtaining a general understanding of user modeling, and an understanding of how to apply user modeling techniques. Students will read seminal papers in the user modeling literature, as well as complete a course project where students build a system that explicitly models the user. (Prerequisites: Knowledge of probability.)

SEME/CS 566. Graphical Models for Reasoning Under Uncertainty

This course will introduce students to graphical models, such as Bayesian networks, Hidden Markov Models, Kalman filters, particle filters, and structural equation models. Graphical models are applicable in a wide variety of work in computer science for reasoning under uncertainty such as user modeling, speech recognition, computer vision, object tracking, and determining a robot's location. This course will cover 1) using data to estimate the parameters and structure of a model using techniques such as expectation maximization, 2) understanding techniques for performing efficient inference on new observations such as junction trees and sampling, and 3) learning about evaluation techniques to determine whether a particular model is a good one. (Prerequisites: CS 534 Artificial Intelligence or permission of the instructor.)

SEME/CS 567. Empirical Methods for Human-Centered Computing

This course introduces students to techniques for performing rigorous empirical research in computer science. Since good empirical work depends on asking good research questions, this course will emphasize creating conceptual frameworks and using them to drive research. In addition to helping students understand what makes a good research question and why, some elementary statistics will be covered. Furthermore, students will use and implement computationally intensive techniques such as randomization, bootstrapping, and permutation tests. The course also covers experiments involving human subjects, and some of the statistical and non-statistical difficulties researchers often encounter while performing such work (e.g., IRB (Institutional Review Board), correlated trials, and small sample sizes). While this course is designed for students in Human Computer Interaction, Interactive Media & Game Development, and Learning Sciences and Technologies, it is appropriate for any student with programming experience who is doing empirical research. (Prerequisites: MA 511 Applied Statistics for Engineers and Scientists or permission of instructor.)

SEME/CS 568. Artificial Intelligence for Adaptive Educational Technology

Students will learn how to enable educational technology to adapt to the user and about typical architectures used by existing intelligent tutoring systems for adapting to users. Students will see applications of decision theoretic systems, reinforcement learning, Markov models for action selection, and Artificial Intelligence (AI) planning. Students will read papers that apply AI techniques for the purpose of adapting to users. Students will complete a project that applies these techniques to build an adaptive educational system. (Prerequisites: CS 534 Artificial Intelligence or permission of the instructor.)

System Dynamics and Innovation Management

Joint Degree Program – M.S., B.S./M.S. and Graduate Certificate

The program is designed to keep students at the forefront of business innovations by learning the essential principles and techniques of system dynamics and by applying them to critical issues in various business environments. The program prepares students to become part of the next generation of business leaders with competency in understanding internal dynamics of complex human systems so they are equipped with the knowledge, tools and skills to strategically influence decision-making in any organizational or societal setting.

Graduates of this program will be able to:

- Model a complex business decision-making situation to better understand the behavior and identify underlying influential factors so as to provide effective and sustainable innovative ideas as part of vital force of change;
- Synthesize and discern the impact of policies and technological solutions in complex systems across interdisciplinary boundaries;
- Demonstrate visionary leadership and management acumen by acquiring the technical, professional and personal knowledge to transform and/or enhance organizations.

Faculty

Khalid Saeed, Social Science and Policy Studies Department, Director of the Program

Mike Elmes, Foisie School of Business, Co-Director of the Program

All faculty in the Foisie School of Business and in the System Dynamics program are affiliated faculty for the SDIM Program.

Programs of Study

M.S., B.S./M.S. and Graduate Certificate

Admissions Requirements

For M.S. SDIM

Applicants must follow the requirements set forth for all WPI graduate applicants: http://www.wpi.edu/admissions/graduate/appl-requirements.html. Specifically, a bachelor's degree is required in any discipline, along with an acceptable score on either GMAT or GRE examination. The admission decision is made based on the overall profile of an applicant. While there is no specific undergraduate major required, we believe students that will most likely succeed in the program will have had academic training and/or work experience in STEM, social science, economics, or operations research/management.

Degree Requirements

For M.S. SDIM

Students pursuing the M.S. SDIM program must complete a minimum of **33** credits of relevant work at the graduate level. These 33 credits must include either a 3-credit Graduate Qualifying Project or a 9-credit M.S. research thesis depending on the degree requirement option selected, in addition to the coursework requirements described below. These M.S. degree requirements are designed to provide a comprehensive yet flexible program to students who are pursuing an M.S. degree exclusively, as well as students who are pursuing combined B.S./M.S. degrees.

Students accepted into the program will be assigned an academic advisor. In consultation with the academic advisor, a student must prepare a *Plan of Study* outlining the selections that the student will make to satisfy the M.S. degree requirements from among the options offered. This Plan of Study must be submitted to the SDIM Program Review Board for approval no later than a student completes 9 credits.

I. Required Courses (21 credits)

Students in the M.S. SDIM program must take 7 required courses: three from the Social Science & Policy Studies Department and four from the Foisie School of Business as follows:

a) Social Science and Policy Studies Department:

SD 550. System Dynamics Foundation: Managing Complexity

SD 551. Modeling Experimental Analysis of Complex Problems

SD 557. Latent Structures, Unintended Consequences and Public Policy

b) Foisie School of Business:

OBC 500. Group and Interpersonal Dynamics in Complex Organizations

FIN 501. Economics for Managers

OIE 500. Analyzing and Designing Operations to Create Value

MIS 500. Innovating with Information Systems

II. Electives (3-9 credits)

Students must take coursework from the electives listed below in order to satisfy the remainder of the 33 credit program requirement. Those opting to pursue the research thesis option will take 3 credits of electives. Those pursuing GQP option will take 9 credits of electives.

While the required courses ensure that students have adequate coverage of essential SDIM knowledge and skills, the wide variety of electives listed below allows students to tailor their degree program to domains and technical areas of personal interest. Students are expected to select electives to produce a consistent program of study. Other courses beyond the pre-approved program electives listed below may be chosen as electives with *prior* approval by the SDIM Program Review Board. Independent study and directed research credits also require *prior* approval by the SDIM Program Review Board.

Relevant System Dynamics Graduate Courses:

- SD 553: Modeling Analysis and Evaluation Techniques
- SD 554: Real World System Dynamics
- SD 556: Strategic Modeling and Business Dynamics
- SD 560: Strategy Dynamics
- SD 562: Project Dynamics
- SD 565: Macroeconomic Dynamics
- SD 590: Special Topics

III. Graduate Qualifying Project (3 credits)/**Thesis** (9 credits)

Students in the M.S. SDIM program must complete one of the following two options:

- **A 3-credit Graduate Qualifying Project (SDIM 598)**: This project can be done in teams or individually, and will provide a capstone experience in applying system dynamics and innovation management skills to a real-world problem. It may be completed in cooperation with a sponsoring organization or industrial partner, and must be approved and overseen by a faculty member affiliated with the SDIM Program. Project advisor may be different from the academic advisor.
- **A 9-credit Thesis (SDIM 599)**: This option consists of an individual thesis research or development project. Exceptional students that wish to pursue a Ph.D. degree are encouraged to select this option. The thesis will be overseen by a committee of at least 3 faculty members chaired by a member affiliated with the SDIM program. The thesis proposal must be approved by the SDIM Program Review Board and the student's thesis committee before the student can register for the research credits. Students must satisfactorily complete a written thesis and publically present the results.

For the B.S./M.S. Degree

Students can also pursue a B.S./M.S. degree combining any undergraduate major with M.S. in SDIM. Students enrolled in the B.S./M.S. program must satisfy all the program requirements of their B.S. degree as well as all the program requirements of the M.S. in SDIM. They may double count 4000-level courses for up to 12 credits of the 33 credit hours required for the M.S. in SDIM. They may also double count 12 credits of their graduate course credit towards meeting their undergraduate degree requirements. The conversion rate between graduate credits and undergraduate credits is stated in both the undergraduate and graduate catalogues. Thus, 18 undergraduate credits will yield 12 graduate credits and 12 graduate credits will yield 18 undergraduate credits. Minimum grade earned in double counted courses must be B. Students must register for B.S./M.S. credit prior to taking the courses, as an instructor may assign extra work for those taking a course for meeting the requirement of both degrees.

In consultation with the academic advisor, students must prepare a *Plan of Study* outlining the selections they will make to satisfy the B.S./M.S. degree requirements, including the courses that will double count. This *Plan of Study* should be submitted for approval to the SDIM Program Review Board by the end of 1st semester of enrollment into the B.S./M.S. program. Students must consult their advisors and the graduate catalog for making course selections.

For Graduate Certificates

A graduate certificate program in SDIM is also available and requires **six** courses (18 credits) per following lists, which contain the seven SDIM required courses described above: 3 must be the required System Dynamics courses and 3 are selected from the 4 required Business courses.

a) Social Science and Policy Studies Department:

SD 550. System Dynamics Foundation: Managing Complexity

SD 551. Modeling Experimental Analysis of Complex Problems

SD 557. Latent Structures, Unintended Consequences and Public Policy

b) Business: 3 courses selected from the following list

OBC 500: Group and Interpersonal Dynamics in Complex Organizations

FIN 501: Economics for Managers

OIE 500: Analyzing and Designing Operations to Create Value

MIS 500: Innovating with Information Systems

Upon completion of this certificate, students will have a good understanding of how system dynamics can be applied to analyzing real-world problems and interpret the implications on decision-making and innovative processes.

Program Delivery

Students can avail themselves of multiple learning (delivery) formats including on-campus, online, or blended and can pursue their degree either on a part-time or full-time basis.

Systems Engineering

http://www.wpi.edu/academics/Online/systems.html

Faculty

Faculty members hold full time positions in a WPI academic department or are adjunct faculty vetted by a WPI academic department head.

F. J. Looft, Academic Director Systems Engineering; Professor; Ph.D., Michigan. Robots and robotic systems, robot sensors, alternative energy systems, systems engineering capstones and education.

S. Doremus, Senior Lecturer; M.S., DePaul University, Certified Project Management Professional (PMP). Product development R&D, enterprise systems, systems integration, decision analysis, risk management, system optimization, project management, telecommunications and information technology.

T. Gannon, Professor of Practice; Ph.D., Stevens Institute of Technology. Information systems engineering, enterprise systems engineering and integration, fault tolerant systems, information and telecommunications technology, systems architecture and design, and systems engineering capstones.

D. Gelosh, Program Director Systems Engineering; Ph.D., University of Pittsburgh. Advancing the overall state of practice for systems engineering, technical leadership, program protection planning and competency models and frameworks.

J. P. Monat, Professor of Practice and Director, Corporate and Professional Education; Ph.D., Stanford University. Systems thinking, emergence and self-organization, system optimization, risk management, decision analysis, project management.

R. S. Swarz, Professor of Practice and Chair, SE Advisory Committee. Ph.D., New York University. SE tools and processes, model-based SE, system architecture, system of systems/complex systems, dependable systems, system security engineering.

S. S. Virani, Teaching Assistant Professor; Ph.D., University of Alabama. Modeling based systems engineering (MBSE), engineering education and team mental models.

Programs of Study

- Master of Science in Systems Engineering
- B.S./M.S. Program in Systems Engineering
- Ph.D. in Systems Engineering
- Graduate Certificate in Systems Engineering
- Graduate Certificate in Systems Engineering Fundamentals
- Graduate Certificate in Systems Thinking
- Advanced Certificate in Systems Engineering

WPI offers graduate levels studies in the field of systems engineering leading to a Master of Science as well as graduate level certificates. These programs are designed to exemplify the WPI tradition of theory and practice and incorporate input from engineers currently practicing systems engineering. The programs integrate content from engineering, science, and management. The M.S. degree is designed to provide students with advanced knowledge of engineering systems and management supplemented with a technology focus. The degree of Doctor of Philosophy is conferred on candidates in recognition of high scientific attainments and the ability to conduct original research. Professional employment in a technological field or industry enhances the student's ability to comprehend the scope and magnitude of the complexity of systems engineering.

B.S./M.S. Program

The Master's degree in System Engineering can be earned by undergraduate students who pursue a five year Bachelor's/Master's degree program in which the Bachelor's degree is awarded in any engineering major at WPI and the Master's degree is awarded in System Engineering. Students who are not engineering majors but who are math or science majors and have a minor in an engineering area should contact the Systems Engineering office and discuss their plans and goals with a faculty member in the Systems Engineering program.

WPI allows the double counting of up to 12 credits for students pursuing a 5-year Bachelor's-Master's Degree program. This overlap can be achieved through proper academic course planning and with the following recommendations for double counting courses.

- Students should plan to take SYS 501 in their fourth year of undergraduate studies and double count the credit toward the M.S. SE program requirement. (3 credits)
- Students should plan to take MIS 576 in their fourth year of undergraduate studies and double count the credit toward the M.S. SE program requirement (3 credits)
- To satisfy the SE Depth Requirement, students should plan to double count any approved combination of 4000 or 500 level engineering, science or math courses that total to at least 6 graduate credits. Per WPI policy: (6 credits)
  - acceptable UG courses are awarded 2 graduate credits
  - acceptable G courses are awarded 2 or 3 graduate credits, depending on the course(s) selected.

Admitted SE B.S./M.S. program students must satisfy all of the requirements of their selected B.S. degree and all the program requirements of the SE M.S. degree. Students interested in the M.S. in Systems Engineering by electing the B.S./M.S. option are strongly encouraged to contact the Systems Engineering office for program planning help.

Admissions Requirements

Admission for the Master's degree and graduate certificates is consistent with the admission requirements listed in the Graduate Catalog for a Master of Science degree. Appropriate undergraduate bachelor's degree majors include but are not limited to Computer Science, Electrical Engineering, Mechanical Engineering, Biomedical Engineering, or Computer Engineering from an accredited university. Admission is determined by a review of the application by faculty from both the Electrical & Computer Engineering Department and the Computer Science Department.

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All SE program applicants should have at least the following mathematics skills:

- An solid understanding of statistics and probability
- A strong background in general engineering mathematics and linear algebra.

Applicants who are accepted and who are judged to not have an appropriate mathematics background may be required to take a graduate level refresher course in mathematics.

Graduate Certificate

A graduate certificate provides qualified students with an opportunity to further their studies in an advanced field. Courses are selected from a range of offerings and give a firm foundation in the field of systems engineering.

Systems Thinking Certificate

This certificate program is designed to meet the needs of a variety of corporations and individuals who are interested in systems engineering education but who may have undergraduate degrees in non-engineering disciplines. The Program of Study shown below presents the requirements for the certificate. Inherent in this program of study is sufficient course selection flexibility for students to, if desired and admitted, be able to continue their graduate studies and earn an M.S. degree in Systems Engineering or SSPS/System Dynamics, depending on student interest and background. For more information consult the WPI website.

Program of Study

The Graduate Certificate in Systems Thinking is composed of 18 credits of graduate coursework, selected as follows.

- The program of study must include the following four graduate courses:
  - SYS 501 Concepts of Systems Engineering
  - SYS 540 Introduction to Systems Thinking
  - SD 550 System Dynamics Foundation: Managing Complexity
  - SD 556 Strategic Modeling and Business Dynamics
- The program of study must also include at least two additional graduate courses tailored to the interests of each student or cohort. Course can be selected from graduate courses from the School of Business, Computer Science, Engineering, Mathematics, System Dynamics and Systems Engineering. Suggested courses include the following:

  If depth in SE is desired:
  - SYS 502 Business Practices
  - SYS 512 Requirements Engineering
  - SYS 579D Engineering Dependable and Secure Systems

  If depth in SD is desired:
  - SD 501 Modeling and Experimental Analysis of Complex Problems
  - SD 562 Project Dynamics

  Additional Suggested Courses:
  - MIS 500 Innovating with Information Systems
  - MIS 576 Project Management
  - OBC 500 Group and Interpersonal Dynamics
  - OBC 537 Leading Change
- Programs of study must be reviewed and approved by an SE or SSPS curriculum committee faculty member.

Graduate Certificate in Systems Engineering

Minimum of 17 credits. For more information, please consult the WPI web.

Graduate Certificate in Systems Engineering Fundamentals

12 credits. For more information, please consult the WPI web.

Advanced Certificate in Systems Engineering

The advanced graduate certificate in Systems Engineering consists of six courses, five in systems engineering and one elective. For more information, consult the WPI website.

Degree Requirements

Masters of Systems Engineering

Degree Requirements

The Master of Science in Systems Engineering is a ten course (30 credit-hour) degree with an emphasis on systems engineering and management supplemented with a technology focus. Table 1 lists the program degree requirements.

Table 1: Credit distribution for the M.S. in Systems Engineering

Component	Credits
Core Requirement	9
Management Requirement	6
Depth Requirement	6
Elective Courses	6
Capstone Experience	3
Total	**30**

Core Requirement (9 credits)

Each student must complete the core of the Systems Engineering degree program which consists of the following three 3-credit graduate systems engineering courses:

- SYS 501 Concepts of Systems Engineering
- SYS 510 Systems Architecture
- SYS 511 Systems Integration and Test

Management Requirement (6 credits)

System engineers need to be aware of, and trained in, managerial methods and practices. Each student must also complete two 3-credit graduate management courses as follows:

- One of MIS 576 Project Management or OIE 541 Operations Risk Management
- Any one course from the following set:
  - MIS 576 Project Management
  - MIS 582 Information Security Systems and Management
  - OIE 541 Operations Risk Management
  - OIE 554 Global Operations Strategy
  - SD 550 System Dynamics Foundation: Managing Complexity

Depth Requirement (6 credits, excluding capstone course/requirement)

To ensure sufficient breadth of knowledge in Systems Engineering, each student must complete a minimum of 15 Systems Engineering graduate credits. In addition to the core required courses noted in the Core Requirement section, each student must complete two additional 3-credit Systems Engineering graduate courses from those listed in Table 2.

Table 2: Current Systems Engineering Graduate Courses

Status	SYS Graduate Courses	
Existing Courses	SYS 501	Concepts of Systems Engineering
	SYS 502	Business Practices
	SYS 510	Systems Architecture and Design
	SYS 511	Systems Integration, Verification and Validation
	SYS 512	Requirements Engineering
	SYS 520	System Optimization
	SYS 521	Model Based Systems Engineering
	SYS 540	Introduction to Systems Thinking
	SYS 579C	Complex Decision Making
	SYS 579D	Engineering Dependable and Secure Systems
	SYS 579S	System of Systems Engineering

Elective Courses (6 credits)

6 credit hours of elective graduate courses can be selected to meet the specific needs of students and organizations. All elective courses must be approved by the student's faculty advisor and can be selected from courses offered by the following departments and programs: Computer Science (CS), Systems Dynamics (SD), any WPI engineering department or program (such as ECE, BME, ME, ChE, EnvE and RBE), the School of Business, and Mathematics (MA).

Capstone Experience (3 credits minimum)

The capstone experience requirement may be satisfied by an instructor-led systems engineering project (SYS 585 Systems Engineering Capstone Experience), an individual directed research project (SYS 598 Directed Research), or a Master's Thesis (SYS 599 Thesis). The capstone experience must not exceed a total of 9 credits. Students may not transfer credit to satisfy the required capstone experience.

Ph.D. in Systems Engineering

Admissions

Information regarding admissions to graduate programs in general, and Ph.D. programs in particular, is available in the Graduate Catalog (page 11, Admission Information and page 13, Application Information).

The preferred program applicant will have an M.S. in Systems Engineering. Applicants who have earned an engineering M.S. degree but not in Systems Engineering, and who have demonstrated SE work experience, will be considered for admission into the Ph.D. program based on a thorough review of their application material. Applicants possessing an M.S. in Systems Engineering from WPI are not required to submit TOEFL scores or the application fee. The Graduate Record Exam (GRE) is not required for admission, but applicants are strongly encouraged to submit GRE scores.

Acceptability of Credit Applicable to the SE Ph.D.

See graduate catalog (p.12, Acceptability of Credit).

Coursework Requirements

Students must complete 60 or more credits of graduate work beyond the credits required for the Master of Science degree. Of the 60 credits, at least 30 credits must be registered under the designation SYS 699.

The doctoral student must meet two distribution requirements for courses in areas outside of Systems Engineering. The specific courses used to meet the distribution requirements are selected in consultation with a student's Research Advisor.

For the first course distribution requirement, doctorial students must take a minimum of 12 credits hours of approved, thematically-related graduate level courses from a Science (including Computer Science), Mathematics, or Engineering program, excluding Systems Engineering. For the second course distribution requirement, doctorial students must take a minimum of 9 credits hours of approved, thematically-related graduate level courses from a Science (including Computer Science), Mathematics, or Engineering program, excluding Systems Engineering, and different from the area selected to satisfy the first course distribution requirement. Courses which are cross-listed between the Systems Engineering program and the course offerings of another department or program cannot be used to fulfill either of these distribution requirements.

Students who enter the Systems Engineering program with a Master of Science Degree in a Science (including Computer Science), Mathematics or Engineering program, but excluding a Systems Engineering Master of Science degree, will be considered to have completed the first course distribution requirement for 12 credit hours of approved, thematically-related graduate level courses. Students who meet this exception will still be required to complete a minimum of 60 credits of graduate work, including the second course distribution requirement noted above, for the Systems Engineering Ph.D. beyond the credits required for the Master of Science degree.

All doctoral students are required to attend and pass two offerings of the SE graduate seminar courses, SYS 596A (fall semester) and SYS 596B (spring semester). Students may enroll in the graduate seminar course in any combination (e.g. two different semesters, or same semester over two years). Enrollment in the graduate seminars is required even if a student has already enrolled and counted seminar credit as part of an M.S. degree program.

Publications

All SE Ph.D. students are encouraged to submit and present their research results at appropriate academic and/or professional conferences.

Research Advisor and Dissertation Committee Selection

The doctoral student is required to select a Research Advisor or multiple Co-Advisors. In consultation with the Systems Engineering Academic Program Chair, the Research Advisor(s) form a Dissertation Committee for the student prior to scheduling the Ph.D. Qualifying Examination (described below). The following rules apply to the committee membership.

- The committee must consist of at least three faculty members if there is a single Research Advisor (or four faculty members if there are two Research Co-Advisors).
- At least one of the committee members must be a full-time, WPI tenured/tenure-track faculty member.
- At least one of the committee members and the Research Advisor (or one of the Research co-Advisors) must hold an earned doctoral degree.
- At least half of the committee members must be Systems Engineering full-time or Adjunct faculty members.
- At least one committee member must be a faculty member not affiliated with the WPI SE Program, or a recognized subject matter expert from industry.

Once the Dissertation Committee has been established, any changes to that committee must be approved by the Research Advisor(s). Changes to the student's Research Advisor(s) must be approved by the Systems Engineering Academic Program Chair. A completed *Research Advisor(s) and Committee Selection* form must be filed with the Systems Engineering Program prior to taking the Qualifying Examination and each time there is a change to the Research Advisor(s) or Dissertation Committee.

Ph.D. Qualifying Examination

The doctoral student is required to successfully complete the Qualifying Examination no later than 18 credits beyond the M.S. degree. The Qualifying Examination is administered by the SE Academic Program Chair and the student's Dissertation Committee. At the discretion of the SE Academic Program Chair, additional faculty outside of the student's Dissertation Committee may also be invited to participate in the examination.

The Qualifying Examination is intended to be an opportunity to evaluate the student's level of academic preparation and identify any shortcomings in the student's background upon entrance to the Ph.D. program. The format and duration of the examination is at the discretion of the SE Academic Program Chair and Dissertation Committee. The examination may be written and/or oral and may include questions to test the general background of the student as well as questions specific to the student's intended area of research. Other formats for this examination will be acceptable if approved by the SE Academic Program Chair in consultation with the Dissertation Committee and the Research Advisor(s).

The SE Academic Program Chair and Dissertation Committee determine the outcome of the Qualifying Examination (Pass, Repeat, or Fail) and any required remediation intended to address shortcomings identified in the student's background.

- A grade of Fail will result in dismissal from the SE graduate program.
- A grade of Repeat requires the student to retake the examination within one year of the date of the initial Qualifying Examination.
- A grade of Pass is expected to also include a summary of any required remediation including, but not limited to, coursework, reading assignments, and/or independent study.
- The only permissible grades if a student takes the Qualifying Examination a second time are Pass and Fail.

Irrespective of the outcome of the examination, a *Qualifying Examination Completion* form, signed by the SE Academic Program Chair and Dissertation Committee members, must be filed with the Systems Engineering Program upon completion of the examination.

Upon successful completion of the Qualifying Examination, each doctoral student must submit a *Ph.D. Program of Study (PoS)* form with the Systems Engineering Program. The program of study should be completed in consultation with, and signed by, the student's Research Advisor(s) and should include specific course work designed to address any shortcomings identified in the student's background during the Examination.

Upon successful completion of the Ph.D. Qualifying Examination, the student becomes a SE Ph.D. candidate.

Area Examination

The doctoral student is required to pass an Area Examination prior to writing a dissertation. The Area Examination is intended to be an opportunity for the student's Research Advisor(s) and Dissertation Committee members to evaluate the suitability, scope, and novelty of the student's proposed dissertation topic. The format of the Area Examination is at the discretion of the student's Dissertation Committee but will typically include a presentation by the student describing the current state of their research field, their planned research activities, and the expected contributions of their work.

Students are eligible to take the Area Examination after they have successfully completed the Ph.D. Qualifying Examination and at least two semesters of coursework (18 graduate credit hours if part-time) in the graduate program. Failure to successfully complete the Area Examination prior to the end of the student's seventh semester (42 graduate credit hours if part-time) after Ph.D. program matriculation will be considered a failure to make satisfactory academic progress and may result in removal from the program.

The Research Advisor(s) and Dissertation Committee determine the Pass/Fail outcome of the Area Examination. A grade of Fail will result in dismissal from the SE Ph.D. graduate program. A grade of Pass may include recommendations for study or remediation. An *Area Examination Completion* form must be signed by the student's Research Advisor(s) and Dissertation Committee Members and filed with the Systems Engineering program Graduate Secretary upon completion of the Area examination.

Dissertation and Defense

The doctoral student must complete and orally defend publicly a dissertation prepared under the general supervision of the Research Advisor(s). The research described in the dissertation must be original and constitute a contribution to knowledge in the major field of the candidate. The Research Advisor(s) and Dissertation Committee shall certify the quality and originality of the dissertation research, the satisfactory execution of the dissertation, and the preparedness of the student for the defense of the dissertation. The Graduate Secretary must be notified of a student's defense at least seven days prior to the date of the defense, without exception. The dissertation defense can be scheduled any time after the end of the semester in which the Area Examination was completed.

Residency Requirements

The student must establish residency by being a full-time graduate student for at least one continuous academic year.

Course Descriptions

All courses are 3 credits unless otherwise noted.

SYS 501. Concepts of Systems Engineering
Systems Engineering is a multifaceted discipline, involving human, organizational, and various technical variables that work together to create complex systems. This course is an introduction and overview of the methods and disciplines that systems engineers use to define, develop, and deploy systems. It includes specific integrated examples, projects, and team building exercises to aid in understanding and appreciating fundamental principles. Topics covered include; Introduction to Systems Engineering; Requirements Development; Functional Analysis and Requirements Allocation; System Architecture and System Design; Integration, Verification and Validation; Trade Studies; Systems Analysis, Modeling and Simulation; Specialty Engineering; Risk Management; and Technical Planning and Management. (Prerequisite: an undergraduate degree in engineering or science, or permission of the instructor)

SYS 502. Business Practices

This course introduces students to the business aspects of Systems Engineering (SE) and is designed to help SE professionals integrate Systems Engineering concepts into a professional business practice environment and to improve systems engineers' understanding fundamental business practices and their relationship to systems engineering.

This course will cover how to prepare and evaluate professional quality business plans, project budgets, financial proposals, timelines and technical outlines. This course will also cover topics such as working with stakeholders; understanding competitive advantage and perceived value of systems engineering; various roles of systems engineers from a business practices perspective; contracting for systems engineering services, how systems engineers impact and are impacted by the various corporate operating divisions, and how to ensure quality control. The course will consist of lectures, case studies, class projects and student presentations.

SYS 510. Systems Architecture and Design

This course will study and contrast various important architectural frameworks, representations, tools, and methodologies in order to provide scalable and flexible approaches for enterprises operating in dynamic and complex environments. Enterprise-level system architecting tools will be discussed and demonstrated. At a minimum, the DoDAF, FEAF, Zachman, and TOGAF architectural frameworks will be discussed in depth. Other topics will include analysis of architectural alternatives to meet physical and logical objectives and providing information and systems assurance in an environment that takes people, processes, and technology into account. Modeling tools such as UML/SysML and the use of model-driven architectures will be presented. Validation of the architecture with stakeholders will be discussed. Methods of identifying risks and opportunities associated with the architectural choice will be explored. Practical examples will be included for illustration. (Prerequisite: SYS 501 Concepts of Systems Engineering or another introductory course in Systems Engineering)

SYS 511. Systems Integration, Verification and Validation

This course examines the use of Systems Engineering principles and best practices with respect to systems and systems-of-systems verification and validation (V&V). V&V processes, activities and methods as they apply across the product lifecycle will be examined. Case studies, papers and exercises will be used to examine the success and failure of verification, validation and test processes. Course topics include 1) How early systems engineering activities and solution sets affect integration, verification, validation and test; 2) V&V activities relative to product development phases; 3) Modeling quality, cost, time and risk; 4) Testing and non-testing methods; 5) V&V planning, execution and reporting; 6) Systems integration; and 7) V&V of critical and complex systems. (Prerequisite: SYS 501 Concepts of Systems Engineering)

SYS 512. Requirements Engineering

Requirements drive system definition and development. Properly managed requirements contribute to project success, while poorly defined and poorly managed requirements often lead to project failure. Modern systems are demanding even more attention to proper requirements definition and management. This course provides processes, techniques, and best practices necessary to develop and manage requirements in today's complex environments. (Prerequisite: SYS 501 Concepts of Systems Engineering. Formerly SYS 579R).

SYS 520. System Optimization

This course covers both the principles and practices of system optimization. The course includes both traditional mathematical treatments of optimization (including linear programming, non-linear programming, integer programming, stochastic methods such as Monte-Carlo methods, multi-objective system optimization, data envelope analysis) and practical, hands-on application with many real-world examples and student projects/exercises. Qualitative as well as quantitative approaches will be discussed. The course begins with an introduction and definitions of system, optimization, and system optimization. It then proceeds to explain the traditional mathematical tools and models used in system optimization including location, allocation, scheduling, and blending models as well as sensitivity analysis and network models. Optimized design is covered next. The course will conclude with several multi-objective optimization problems. Student projects and real-world examples will be heavily emphasized. A technical undergraduate degree (B.A. or B.S. or equivalent) is a prerequisite for this course. (Prerequisite: SYS 501.)

SYS 521. Model-Based Systems Engineering

Model-based systems engineering (MBSE) formalizes the practice of systems engineering through the use of models. This course is intended to answer the why, what and how of MBSE and provides background and motivation for transitioning from a document centric approach to a model-based approach to systems engineering. The course provides a foundation for MBSE by introducing SysML as a descriptive language for modeling systems and a method for applying SysML to support the specification, architecture design, and analysis of complex systems. The course also introduces other important aspects of implementing MBSE, including organizational and project planning considerations. The course includes a combination of slide presentations to introduce the fundamentals, coupled with class exercises and a class project to help the student grasp the fundamentals. A modeling tool is expected to be used for the class project. (Prerequisite: SYS 501 Concepts of Systems Engineering.)

SYS 540. Introduction to Systems Thinking

Systems Thinking provides an arsenal of tools that enable program managers and systems engineers to better identify, understand, and control systems, and to improve their performance. In this course, we will study system identification and delineation, causal loops and feedback, system leverage points, delays and oscillations, mental models and unintended consequences, emergent properties, patterns, events, and self-organization, and use these tools to improve the performance of engineering, biological, business, and complex social systems. We will explore great system failures, how they might have been avoided, and how we can learn from them in developing and participating in current systems. Finally, we will learn how systems thinking explains the conflicting behavior of individuals, departments, businesses, and countries.

SYS 579. Special Topics

SYS 585. Systems Engineering Capstone Experience

One of the central priorities in WPI's educational philosophy is the application of academic skills and knowledge to real-world problems. The capstone project represents a substantive evaluation and application of coursework covered in the program. Students are encouraged to select projects with practical significance for the advancement of their company's competitive position as well as their own personal development. The project is administered, advised, and evaluated by WPI as part of the learning experience, but students are encouraged to seek mentorship from experienced colleagues in the Systems Engineering profession. The presence of or degree of participation from a mentor is made at the discretion of the student or the organization sponsoring the program. (Prerequisite: SYS 501 Concepts of Systems Engineering)

SYS 596A and SYS 596B. Graduate Seminars

The graduate seminar series will be presented by recognized experts in various fields of Systems Engineering and related disciplines. All SE Ph.D. students are required to take two offerings of the SE seminar course. Each offering will be graded Pass/Fail.

SYS 597. Independent Study

Approved study of a special subject or topics selected by the student to meet his or her particular requirements or interests. Independent study students will work under the direct supervision of a WPI ECE, ME or CS faculty member.

SYS 598. Directed Research

Directed research students will work under the direct supervision of a WPI ECE, ME or CS faculty member on an experimental or theoretical problem which may involve an extensive literature search, experimental procedures and analysis. A comprehensive report in the style of a technical report or paper and an oral presentation are required.

SYS 599. Thesis

(Prerequisite: Accepted to Systems Engineering M.S. degree program.)

SYS 699. Ph.D. Dissertation

Reserved for Ph.D. candidate research. Approval of the Ph.D. research advisor is required.

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Notice of Disclaimer

WPI reserves the right to make changes in policy, regulations, tuition and fees subsequent to the publication of this material. For a current description of the WPI policies and procedures, tuition and fees, please contact the Graduate Studies and Enrollment Office.

Notice of Nondiscriminatory Policy as to Students

It is the policy of WPI that each qualified individual shall have equal opportunity in education, employment and services at WPI. As a matter of practice and policy, and in accordance with the Civil Rights Act of 1964, Title IX of the Education Amendments of 1972, Section 504 of the Rehabilitation Act of 1973, and other state and federal laws, WPI does not discriminate on the basis of race, color, age, sex, ancestry, religion, national origin, sexual orientation, family status, disability or membership in the armed services, in recruiting and admitting students, awarding financial aid, recruiting and hiring faculty and staff, or in operating any of its programs and activities.

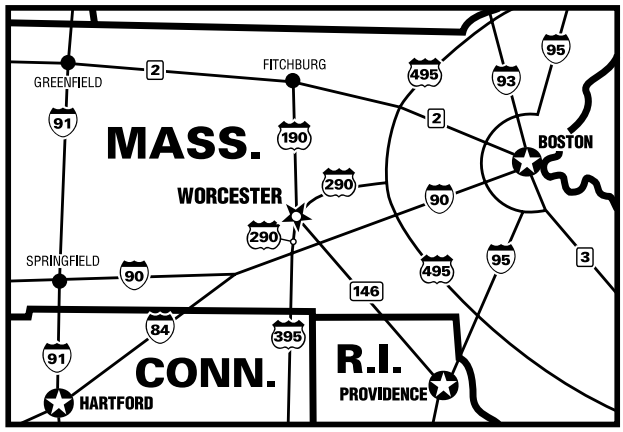
Notice of Accreditation

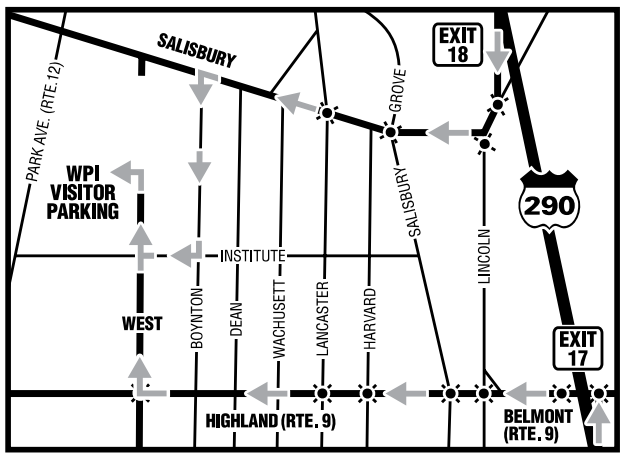
WPI is accredited as an institution by the New England Association of Schools and Colleges Inc., a nongovernmental, nationally recognized organization whose affiliated institutions include elementary schools through collegiate institutions offering post-graduate instruction. In addition, undergraduate programs leading to majors in computer science, chemical, civil, electrical, industrial, manufacturing and mechanical engineering are accredited by the Engineering Accreditation Commission of the Accreditation Board for Engineering and Technology (ABET). The Chemistry and Biochemistry Department and its program are approved by the American Chemical Society for a major in chemistry. The School of Business is accredited by The Association to Advance Collegiate Schools of Business (AACSB).

Driving Directions

To WPI's Worcester Campus
100 Institute Road, Worcester, MA

The top map will guide you to I-290. Exit at 17 if eastbound or 18 if westbound. Using the bottom map, follow the arrows to the WPI campus.





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