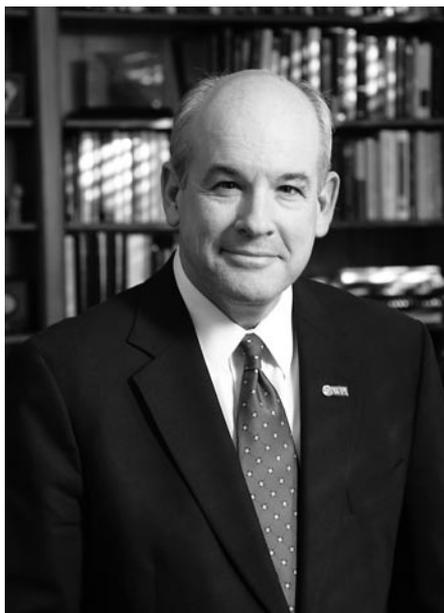




COURSE CATALOG  
WORCESTER POLYTECHNIC INSTITUTE



# GRADUATE: 2010-11



## President's Message

### Value and Purpose

The richness of the WPI experience has always emanated from the purposeful nurturing of students by faculty well informed in the potential applications of knowledge, fruitful interactions among students, and faculty research focused on the important, not just the interesting. From Robert Goddard's introduction of liquid-fueled rocketry, to Richard Whitcomb's designs for modern jet aircraft, to Dean Kamen's miraculous prosthetic devices, the overarching goal and achievement of the people of WPI have been to create value across a wide spectrum of human need.

A national doctoral university with a heritage of educational innovation, WPI delivered its first graduate program in 1893. To this day, our graduate programs foster collaboration within and across the academic disciplines, and encourage partnerships with industry, government laboratories, and other universities. WPI's highly accomplished faculty is committed to the personal and intellectual development of our students. It is no wonder that our students graduate with the knowledge and skills they need to excel in their careers – from renewable energy and regenerative medicine to information security and fire protection engineering.

To quote one of our 2010 graduates, Roseann Gammal, "WPI has provided me with the knowledge to succeed, the confidence to lead, and the courage to make a difference." On that note, I invite you to take full advantage of WPI's exceptional graduate and research programs. I am confident that you will find they offer you the knowledge, the skills and the experience you need for advanced study, for career development, and, ultimately, for making a difference in the world.

Sincerely,

Dennis D. Berkey

# Graduate Calendar 2010-2011

		S	M	T	W	R	F	S			S	M	T	W	R	F	S		
<b>FALL</b>	<b>AUG</b>	25	26	27	28	29	30	31	<b>FEB</b>	6	7	8	9	10	11	12	<b>SPRING</b>		
		1	2	3	4	5	6	7		13	14	15	16	17	18	19			
		8	9	10	11	12	13	14		20	21	22	23	24	25	26			
		15	16	17	18	19	20	21		27	28	1	2	3	4	5			
		22	23	24	25	26	27	28		6	7	8	9	10	11	12			
		29	30	31	1	2	3	4		13	14	15	16	17	18	19			
	<b>SEPT</b>	<b>MAR</b>	5	6	7	8	9	10	11	20	21	22	23	24	25	26			
			12	13	14	15	16	17	18	27	28	29	30	31	1	2			
			19	20	21	22	23	24	25	3	4	5	6	7	8	9			
			26	27	28	29	30	1	2	10	11	12	13	14	15	16			
			3	4	5	6	7	8	9	17	18	19	20	21	22	23			
			10	11	12	13	14	15	16	24	25	26	27	28	29	30			
<b>OCT</b>	<b>APR</b>	17	18	19	20	21	22	23	1	2	3	4	5	6	7	<b>APRIL 18 PATRIOTS DAY</b>			
		24	25	26	27	28	29	30	8	9	10	11	12	13	14				
		31	1	2	3	4	5	6	15	16	17	18	19	20	21				
		7	8	9	10	11	12	13	22	23	24	25	26	27	28				
		14	15	16	17	18	19	20	29	30	31	1	2	3	4				
		21	22	23	24	25	26	27	5	6	7	8	9	10	11				
<b>NOV</b>	<b>MAY</b>	28	29	30	1	2	3	4	12	13	14	15	16	17	18	<b>Graduation</b>			
		5	6	7	8	9	10	11	19	20	21	22	23	24	25				
		12	13	14	15	16	17	18	26	27	28	29	30	1	2				
		19	20	21	22	23	24	25	3	4	5	6	7	8	9				
		26	27	28	29	30	31	1	10	11	12	13	14	15	16				
		2	3	4	5	6	7	8	17	18	19	20	21	22	23				
<b>DEC</b>	<b>JUNE</b>	9	10	11	12	13	14	15	24	25	26	27	28	29	30	<b>E</b>			
		16	17	18	19	20	21	22	31	1	2	3	4	5	6				
		23	24	25	26	27	28	29	7	8	9	10	11	12	13				
		30	31	1	2	3	4	5	14	15	16	17	18	19	20				
		12	13	14	15	16	17	18	26	27	28	29	30	1	2				
		19	20	21	22	23	24	25	3	4	5	6	7	8	9				
<b>JAN</b>	<b>JULY</b>	26	27	28	29	30	31	1	10	11	12	13	14	15	16	<b>JULY 4 INDEPENDENCE DAY</b>			
		2	3	4	5	6	7	8	17	18	19	20	21	22	23				
		9	10	11	12	13	14	15	24	25	26	27	28	29	30				
		16	17	18	19	20	21	22	31	1	2	3	4	5	6				
		23	24	25	26	27	28	29	7	8	9	10	11	12	13				
		30	31	1	2	3	4	5	14	15	16	17	18	19	20				
<b>FEB</b>	<b>AUG</b>	6	7	8	9	10	11	12	20	21	22	23	24	25	26				
		13	14	15	16	17	18	19	27	28	29	30	31	1	2				

# Table of Contents

President’s Message . . . . .	1
Graduate Calendar . . . . .	2
About the University and the Community . . . . .	4
Graduate Programs by Department/Program . . . . .	5
Graduate Programs by Degree . . . . .	6
Graduate and Advanced Graduate Certificates . . . . .	8
Corporate and Professional Education . . . . .	10
Advanced Distance Learning Network (ADLN) . . . . .	11
Admission Information . . . . .	12
Application Requirements . . . . .	15
Financial Information . . . . .	16
Grading System and Academic Standards . . . . .	17
Registration Information and Procedures . . . . .	20
Degree Requirements . . . . .	22
Theses and Dissertations . . . . .	24
Student Services . . . . .	24
Academic Departments and Programs . . . . .	27
Biology and Biotechnology . . . . .	28
Biomedical Engineering . . . . .	30
School of Business . . . . .	35
Chemical Engineering . . . . .	44
Chemistry and Biochemistry . . . . .	48
Civil and Environmental Engineering . . . . .	51
Computer and Communications Networks . . . . .	58
Computer Science . . . . .	60
Electrical and Computer Engineering . . . . .	66
Fire Protection Engineering . . . . .	75
Interdisciplinary Programs . . . . .	78
Learning Sciences and Technologies . . . . .	80
Manufacturing Engineering . . . . .	84
Materials Process Engineering . . . . .	87
Materials Science and Engineering . . . . .	88
Mathematical Sciences . . . . .	93
Mechanical Engineering . . . . .	103
Physics . . . . .	115
Robotics Engineering . . . . .	117
Social Science & Policy Studies . . . . .	121
Campus Telephone Numbers . . . . .	127
Index . . . . .	130
Campus Directions . . . . .	131
Campus Map . . . . .	132

# About the University and the Community

## Graduate Study at WPI

WPI, the nation's third oldest independent technological university, was also among the first to recognize the need to provide science, engineering, and management professionals with graduate-level educational opportunities on a part- and full-time basis.

Opportunities for graduate study at the university include master's and doctoral degree programs, graduate certificates, and advanced study for non-degree students. Off-campus study, available in several academic areas through WPI's Advanced Distance Learning Network, brings graduate education to the workplace or home.

At WPI, part-time graduate students benefit from the same faculty and academic quality as full-time students. In addition, all graduate students have access to the same state-of-the-art facilities and modern laboratories, including the new 125,000-square-foot Life Sciences and Bioengineering Center. This facility, home to graduate research programs from four academic departments, is the first building to be built at Gateway Park, an 11-acre life sciences-based campus the university is developing a short distance from campus.

WPI addresses the requirements of full-time students, technically-oriented professionals, and secondary school educators with a wide range of advanced courses and programs known for their flexibility, quality, and optimal accessibility.

## The University

Since its founding in 1865, WPI has emphasized the application of theoretical knowledge to practical, real-world problems, an approach to education reflected in the university's motto: *Lehr und Kunst*, or Theory and Practice. The university awarded its first master of science degree

(in electrical engineering) in 1893. Its first doctoral degree (in natural science) was granted in 1904. New programs have been added regularly in response to the growing capabilities of the university and the changing needs of the professions. Currently, WPI offers nearly 50 master's and doctoral programs.

More than 40 years ago, responding to the demanding work schedules of professionals, WPI developed the first of what is today an extensive array of part-time graduate programs. Each is designed to accommodate the professional development needs of those with significant career and family commitments.

The current student body of 3,700 includes more than 1,000 graduate students. They are taught by approximately 320 faculty.

## Colleges of Worcester Consortium

Through the Colleges of Worcester Consortium, the area's 20,000 students have access to all the educational benefits of 13 public and private accredited colleges and universities in central Massachusetts, including eight four-year colleges with graduate programs, a medical school, and a veterinary school, as well as several other specialized institutions in the area. Consortium members and associates whose facilities and programs have been particularly useful to WPI graduate students include Assumption College, Clark University, College of the Holy Cross, the Cummings School of Veterinary Medicine at Tufts University, the University of Massachusetts Medical School, and Worcester State College. Cross-registration in courses and the use of special laboratory facilities are encouraged. The consortium operates a free bus service for transporting students between the colleges.

## Locations

WPI is set on an 80-acre hilltop campus situated in a residential section of Worcester, Massachusetts, New England's third largest city. The campus is within a region known for its concentration of high-technology, healthcare, biotechnology, and biomedical engineering research and industry.

Worcester, a city of 170,000, is distinguished by its many colleges and for such cultural landmarks as the Worcester Art Museum, which houses one of the finest collections in the country, and the world-renowned American Antiquarian Society; both are adjacent to WPI. Also nearby are the historic Higgins Armory Museum and the Ecotarium, a museum dedicated to environmental exploration.

Music is well represented by several excellent choruses, a symphony orchestra, and concerts performed by internationally recognized artists in Mechanics Hall, one of the country's finest concert halls. The city is also home to several professional and amateur theater companies. The 15,500-seat DCU Center hosts a wide variety of entertainment and sports events.

Located in the heart of New England, Worcester is within an easy drive of many historical sites, cultural centers, and recreational facilities. These include Boston's Freedom Trail, Fenway Park, the beaches of Cape Cod and Maine, the ski slopes of New Hampshire and Vermont, the Berkshires, and several major metropolitan areas featuring world-class museums, concert halls, and professional sports teams.

# Graduate Programs by Department/Program

## Biology and Biotechnology\*

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

## Biomedical Engineering\*

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

## School of Business

Graduate Certificate  
Master of Business Administration  
(M.B.A.)  
Master of Science in Information  
Technology  
Master of Science in Marketing and  
Technological Innovation  
Master of Science in Operations Design  
and Leadership

## Chemical Engineering

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 and  
Communications Networks  
Master of Science in Robotics  
Engineering  
Advanced Certificate  
Ph.D. in Computer Science  
Ph.D. in Robotics Engineering

## Electrical and Computer Engineering

Graduate Certificate  
Master of Engineering in Electrical  
Engineering  
Master of Science in Electrical  
Engineering  
Master of Science in Systems  
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

## Interdisciplinary Studies

Master of Science in Learning Sciences  
and Technologies  
Master of Science in Interdisciplinary  
Studies  
– Impact Engineering  
– Manufacturing Engineering  
Management  
– Power Systems Management  
– Systems Modeling  
Ph.D. in Interdisciplinary Studies  
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

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

## Mathematical Sciences

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

## Physics

Master of Science in Physics  
Ph.D. in Physics

## Robotics Engineering

Master of Science in Robotics  
Engineering

## Social Science and Policy Studies

Graduate Certificate in System  
Dynamics  
Master of Science in System Dynamics  
Interdisciplinary Ph.D. in Social Science

\*Fall semester admission only

# 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. Please see the list of programs on page 5 for details.

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.

## The Doctor of Philosophy (Ph.D.) Programs

Available in the following disciplines:

- Biochemistry
- Biotechnology
- Biomedical Engineering
- Chemical Engineering
- Chemistry
- Civil Engineering
- Computer 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

## Master of Science (M.S.) Programs

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

- Applied Mathematics
- Applied Statistics
- Biochemistry\*
- Biology/Biotechnology\*
- Biomedical Engineering
- Chemical Engineering\*
- Chemistry\*
- Civil Engineering
- Computer Science
  - Specializing in Computer and Communications Networks (CCN)
- Construction Project Management
- Electrical and Computer Engineering
- Environmental Engineering
- Financial Mathematics
- Fire Protection Engineering
- Industrial Mathematics
- Information Technology
- Interdisciplinary Studies
  - Impact Engineering
  - Manufacturing Engineering Management
  - Power Systems Management
  - Systems Modeling
- Learning Sciences and Technologies
- Marketing and Technological Innovation
- Manufacturing Engineering
- Materials Process Engineering
- Materials Science and Engineering
- Mechanical Engineering
- Operations Design and Leadership
- Physics
- Robotics Engineering
- System Dynamics
- Systems Engineering

*\*available only on a full-time basis*

## Master of Engineering (M.E.) Programs

Offered in:

- Biomedical Engineering
- Civil Engineering
  - Environmental Engineering
  - Master Builder Program
- Electrical Engineering

## Master of Business Administration (M.B.A.) Program

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 School of Business at 508-831-5218, or on the web at [mgt.wpi.edu/Graduate/mbatech.html](http://mgt.wpi.edu/Graduate/mbatech.html).

## Master of Mathematics for Educators (M.M.E.) Program

WPI offers a Masters 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.

## 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 MS degree after only five years of full-time work (i.e., typically one year after completion of the BS). Students often obtain the BS and MS in the same field or department, but with careful planning some students complete the combined BS/MS program in two different fields; the combination of a BS in Civil Engineering and an MS in Fire Protection Engineering is a common example. (Throughout this section, "MS" will be used to refer to all Master's-level degrees; most students who complete the combined program obtain the MS).

A similar BS/MBA program is available through the School of Business, but few students elect this option because they lack the professional business experience to gain the full benefits of WPI's MBA program. Students who may be interested in this joint degree program should discuss their goals with the Director of Graduate Management Programs.

### Planning Your Program

Because BS/MS 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 BS/MS 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 MS 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 BS/MS 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 BS/MS program. Sometimes the MQP provides a foundation for a thesis. In cases where the BS and MS 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 BS/MS 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 BS/MS 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 BS/MS 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 BS and the MS, 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 BS/MS 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 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 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 BS/MS program, approved undergraduate courses are assigned graduate credit with a conversion rate of 1/3 WPI undergraduate unit = 3 graduate credit hours, while graduate courses applied toward the undergraduate degree are awarded undergraduate credit with a conversion rate of 1 credit hour = 1/9 undergraduate unit.

### Interdisciplinary Master's and Doctoral Programs

WPI encourages the formation of interdisciplinary master's and doctoral programs to meet new professional needs or the special interests of particular students. For specific information on interdisciplinary master's and doctoral programs (see page 78).

# 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 graduate certificate programs: the Graduate Certificate Program (GCP) and the Advanced Certificate Program (ACP).

## Graduate Certificate Program

The Graduate Certificate Program (GCP) 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 look for related background when making admission decisions. GCP students are required to complete four to six courses totaling 12 to 18 credit hours in their area of interest. GCP 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 departments:

- Biomedical Engineering
- Civil and Environmental Engineering
- Computer Science
- Electrical and Computer Engineering
- Fire Protection Engineering
- Management
- Manufacturing Engineering
- Materials Science and Engineering
- Mathematical Sciences
- Social Science and Policy Studies

Additional programs may be developed in consultation with an academic adviser. For the most current listings go to <http://grad.wpi.edu/+certificate>.

## Advanced Certificate Program

The Advanced Certificate Program (ACP) 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 ACP 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.

ACP's are available in the following departments:

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

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

## Application Process

Application to the GCP and ACP 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 during their first semester and must complete their program within one year. Applications are available on line at <http://grad.wpi.edu/+certificate>.

## 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 cannot retroactively apply to a certificate program. Only two courses taken prior to application to a certificate program may be counted toward a certificate program. If a student goes beyond the second course as a non-degree student, then those courses cannot be applied to a graduate certificate. However, the credits may be applied to a WPI graduate degree program. A GCP or ACP Certificate will not be awarded without acceptance into a program.

## Registration Procedures

GCP and ACP 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 GCP and ACP students are the same as for all other WPI graduate students.

## Program Planning

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 Plan of Study form is available online ([grad.wpi.edu/+certificate](http://grad.wpi.edu/+certificate)). 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 GCP or ACP 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 GCP or ACP requires a cumulative grade point average of 3.0 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.

U.S. citizens will have four years from the date of matriculation to complete their program. International students must complete their program within one academic year.

## **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 GCP and ACP 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 works with leading organizations to maximize the value of their education and training investment by aligning program content with specific business and industry needs. At WPI, we take a collaborative approach to developing programs for our clients, realizing that every organization has unique needs that are specific to its competitive environment. Our portfolio of offerings range from one-day workshops to two-year graduate degree programs, and all of our programs are built on the premise of delivering education that is integrated, applied and relevant to both the participating student and sponsoring company. This practical approach further enhances the value derived by organizations in providing employees with the knowledge and skills that can be directly applied to their workplace challenges.

In addition to the direct benefit of individual development, WPI's corporate programs provide:

- Increased employee retention as a result of a demonstrated commitment and investment in employee education
- An effective recruiting tool to attract new talent in a competitive market
- Focused content that directs educational spending to the areas of highest need, at the right time
- Increased interaction among employees from various functions across the company

WPI's corporate programs take on many forms. Programs can be focused on a single topic or expanded to encompass an entire discipline or integrate complementary disciplines. We work with companies to determine the content areas to meet their needs and then develop programs to effectively deliver results.

## Corporate Graduate Programs

For decades WPI has worked with corporations to develop graduate and undergraduate programs to improve the skills of their employees. WPI can offer custom programs on-site, as well as through our distance learning network.

Companies work with one of our experienced staff to develop programs that meet their needs.

- Programs can range from a single course, to a tightly focused graduate or undergraduate certificate program, to a full graduate degree program.
- Programs can focus in several disciplines including science, engineering, technology, and management.
- Interdisciplinary programs can combine related content that spans many academic disciplines, resulting in programs that meet an organization's unique requirements and challenges from both a technical and managerial perspective.
- All courses taught at corporate sites will include the same material and concepts as on-campus courses, but examples used in courses can be customized for each company's needs.

Courses for WPI's Corporate and Professional Education programs are taught by the same faculty as our on-campus programs. All of our faculty members are experts in their fields and many are working on cutting-edge research in their disciplines. Many faculty members are also active members in the professional community through research partnerships, consulting services and business ventures. Corporate Education takes care in selecting professors to match their academic and professional acumen with the needs of individual organizations.

Following is a list of customized graduate programs developed for specific companies. Contact Corporate and Professional Education at 508-831-5517 or [www.cpe.wpi.edu](http://www.cpe.wpi.edu) to learn more about a customized education solution for your company and industry.

- MBA
- Fire Protection Engineering
- Systems Engineering
- Manufacturing Engineering
- Mechanical Engineering
- Bioscience Regulations Management
- Power Systems Management
- Operations Design and Engineering
- Information & Data Security
- Analog Electronics

## Executive Education

The Executive Education programs at WPI Corporate and Professional Education offer participants three different levels to select from based on experience and needs. Our outcome-based course designs, combined with practical real world applications, provide students with an engaging, world-class learning experience. As a business partner in executive education, we strive to create and deliver open-enrollment or tailored corporate programs that empower participants with immediately actionable skills and knowledge. Whether an individual is looking for professional development in a specific area, or an HR representative or team leader is looking for a solution for a group of employees, we work with them to discuss interests and needs in executive education.

- **Introduction to Management & Communications Certificate Program** features the latest essential skills necessary for new supervisors and managers to be successful in their organizations. Each segment includes specific tools and techniques that can be put to use immediately upon return to the workplace.
- **Advanced Management Program** is designed for professional managers who have several years of experience and would like to enhance their skills. Topics include managing human performance, strategic thinking, productivity management, financial acumen, decision making, innovation and project management.

- **Executive Leadership Program** shortens the learning curve for new leaders by developing the skills needed to achieve excellence as a cross-functional executive. The program is designed especially for senior managers who have been targeted to assume significant managerial responsibilities. Participants will acquire the skills needed for managerial success such as strategy formulation, negotiation, conflict resolution, decision-making, implementing change and managing culture.

## Professional Development Workshops

WPI provides career training and development to individuals and organizations, including both CEU-based and non-credit programs, seminars, and workshops. There are over 50 workshops to choose from that are all designed to deliver the skills needed to stay competitive. WPI's results-oriented programs have been providing management and technical professionals with proven tools and techniques needed to exceed performance goals for over 28

years. There are a wide variety of courses on topics that are important to career advancement and success in many organizations. An example of topics are: project management – 8 courses; process improvement – 9 courses; six-sigma – 6 courses; lean enterprise – 11 courses; geometric dimensioning & tolerancing – 7 courses; and management development – 10 courses. We also offer customized training to meet an organization's specific training needs.

# Advanced Distance Learning Network (ADLN)

## Distance Learning at WPI

For more than thirty years, WPI has delivered high-quality distance education to graduate students around the world. Our first distance programs were available on videotape; the Internet now provides access to course work, professors, and fellow students. Distance students apply for admission to the WPI program of their choice as there is no differentiation between campus and online programs. Once admitted to WPI, students may take any distance course that is appropriate to their WPI program. All students can take distance courses and, within a given program's requirements, can combine on campus and distance courses.

## Online Programs and Courses

Via the Web, WPI delivers the same courses, content and material that you receive on campus. The online and campus programs are not separate programs, but the same program. WPI offers a selected number of online courses each semester, so students located outside of Worcester can further their education via the Internet. Online students have 24/7 access to their courses and are expected to maintain a weekly presence in the WPI course web site. Regular access to a high speed Internet access via a PC based computer is the only technical requirement.

## Programs of Study

By taking courses through the Advanced Distance Learning Network, students can complete graduate degrees and graduate certificates. The specific programs that are available online are listed at [www.online.wpi.edu](http://www.online.wpi.edu).

## Student Services

Online students have access to the same services as students located on campus. WPI's Distance Learning Office provides students with personalized assistance and acts as a conduit to all other university offices. Among the University services available are academic advising, technical helpdesk, library services, bookstore, and career placement and counseling for degree seeking students. Contact can be made through the web, by phone, and by email.

## Faculty

The professors teaching distance courses are the same highly qualified faculty who teach in WPI's campus-based programs.

## Tuition and Fees

Distance learning courses carry the same rate as on-campus courses. Students wishing to earn Continuing Education Units (CEUs) instead of graduate credit may opt to audit courses at half tuition.

## Financial Aid

Loan-based aid is available. Students must be registered on a half-time basis (two courses per semester) or greater for federal loan programs. See page 16 for loan information. Other loans for 3-credit courses are available.

## Contact and Information

**Pamela Shelley**, Assistant Director,  
Advanced Distance Learning Network  
Worcester Polytechnic Institute  
100 Institute Road  
Worcester, Massachusetts 01609-2280  
U.S.A.

508-831-6789 (voice)

508-831-5717 (fax)

[online@wpi.edu](mailto:online@wpi.edu)

[www.online.wpi.edu](http://www.online.wpi.edu)

# Admission Information

## Applying to WPI

Prospective graduate students submit their applications for WPI's science, engineering, and management programs online. Links to the various applications can be found at <http://grad.wpi.edu/+apply>.

Each department requires different credentials for admission. A table of each department's requirements can be found on page 15.

WPI admission requirements include the following:

- A completed Application for Admission to Graduate Study, available only online at [grad.wpi.edu/+apply](http://grad.wpi.edu/+apply). Please note: there are three separate applications for (1) engineering, science, social sciences, and interdisciplinary studies, (2) management programs, and (3) corporate and professional education programs.
- A non-refundable \$70 application fee (waived for WPI alumni and current WPI undergraduates).
- Official college transcripts in English from all accredited degree-granting institutions attended.
- Three letters of recommendation (and/or other references) from individuals who can comment on the applicant's qualifications for pursuing graduate study in the chosen field. We strongly encourage students to use the online application program to invite their recommenders to submit letters.
- Several programs require a statement of purpose (see page 15). This is a brief essay discussing background, interests, academic intent, and the reasons the applicant feels s/he would benefit from the program.
- Proof of English language proficiency must be submitted by all applicants for whom English is not the first language. In order to prove English language proficiency, 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). The minimum scores for admission are:

TOEFL: 213 (computer based test)  
550 (paper-based test)  
79-80 (internet-based test)

IELTS: 6.5 overall band score with no sub-score lower than 6.0

*These are the minimum scores for admission to WPI; higher scores are required for teaching assistants.*

Applicants who have completed two years of full-time study in 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](http://www.toefl.org). For more information on the IELTS, or to take the exam, go to: [www.ielts.org](http://www.ielts.org).

- Some departments require the Graduate Record Examination (GRE). Consult the table on page 15 to determine your department's expectations. There is no WPI-wide minimum GRE score for admission. WPI's school code for the GRE is 3969.

Applicants will receive information explaining how they can check the status of their applications after they submit the forms online. It takes approximately one week for the forms to be entered into WPI's database. After this time, the applicant will have access to their information.

Unless the student is otherwise notified, the Graduate Admissions office will retain incomplete applications for one year after the application was started. The Office reserves the right to cancel an incomplete application at anytime, but it will continue to hold the incomplete forms in its files for a year.

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

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. A final transcript showing that the degree was awarded must be submitted to the Office of Graduate Admissions before the student enrolls.

## Priority Deadlines

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 15th to ensure consideration. Applications that are completed during the two weeks following January 15th will also receive the earliest consideration for funding.

With each passing month the availability of funds decreases, so applications should be completed, if possible, during the two-week processing period that runs from January 15th to January 31st.

A small number of programs also offer assistantships that begin in January. Applicants seeing admission to the Spring semester with funding should submit their credentials by October 15th to receive consideration for these funds.

Applicants who are not seeking funding may apply at any time.

If you are interested in securing a student loan, please contact the WPI Office of Financial Aid after you have accepted your offer of admission.

## Admission

Each department, program, or sponsoring group is responsible for making admissions decisions. Their decisions are communicated to the applicants by the Office of Graduate Admissions.

Sometimes a department will admit a student to a degree program that differs from the program specified in the student's application. Most typically, a department will admit a PhD 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 PhD program in the future.

An admitted 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.

An admitted MS student who wants to pursue a PhD in his or her home department can be admitted to the PhD program without completing a new application. Instead, the graduate coordinator or department chair will write a letter to the Dean of Graduate Studies, in care of his assistant in the Office of Graduate Studies, to the effect that the student has met the qualifications for admission to the PhD program. This letter will be copied to the Office of Graduate Admissions, the Registrar, and the departmental graduate studies committee.

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.

### **Conditional Admission**

Conditional admission is offered to Conditional admission is offered to students who satisfy many of the criteria for admission to a program, but who lack some specific pre-requisite or set of qualifications for graduate study. Typical deficiencies include inadequate preparation in English (for international students), an insufficient

background in mathematics, or incomplete training in the student's desired field of study.

The conditionally admitted student will be apprised of the conditions which must be met---usually a course or series of courses completed with a specified minimum grade---before he or she can be fully admitted to a program. In many cases, students fulfill these conditions either before they arrive at WPI or during their first year of study. They should consult with their graduate coordinator to discuss the best option for meeting the conditions that have been set. Each department monitors the progress of the conditionally admitted student and determines when the conditions of full admission have been met.

### **Confirmation of Admission**

The letter of admission from the Office of Graduate Admissions indicates the semester for which admission is granted. The letter also asks the student to either accept or decline the offer of admission by a specified date by completing the Graduate Admission Response Form. Students who plan to attend are required to submit a non-refundable deposit of \$500, which will be credited to their tuition when they arrive.

### **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.

### **Transfers and Waivers**

A student may petition to use graduate courses completed at other 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 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 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.

### Three-Year Bologna-Process Degrees

WPI welcomes applications from prospective graduate students who have three-year Bologna-compliant undergraduate degrees from European universities.

Applicants who hold these credentials will be evaluated for regular admission on a case-by-case basis. They may be admitted conditionally if they require further preparation for graduate study. Please consult the departmental web pages to learn more about graduate admissions expectations and standards in your field of study.

### Admission to Interdisciplinary Doctoral Programs

WPI encourages interdisciplinary research. Students may apply for admission to interdisciplinary studies directly, but students interested in such options should do so with the assistance of WPI faculty, as these programs require internal sponsorship (see Interdisciplinary Doctoral Programs, pages 5 and 78).

### Advanced Study for Non-Degree Students

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.

# Application Requirements

## Certificate Applications

Applicants to all graduate certificate and advanced certificate programs are required to submit to the Graduate Admissions Office:

1. An application form,
2. A \$70 application fee, and
3. Official transcripts from all colleges or universities attended.

*Note: Contact department for additional requirements.*

## Degree Applications

In addition to the items listed at left, the information listed below is required for application to all graduate degree programs. They are organized by academic department and program.

(Management students should consult with the Graduate Management Program Office for application requirements.)

Department/Program	GRE	Statement of Purpose	Three Letters of Recommendation	TOEFL or IELTS*
Biology and Biotechnology <i>Fall semester admission only</i>	<b>Required</b> for all applicants	<b>Required</b> for all applicants	<b>Required</b> for all applicants	<b>Required</b> for all applicants for whom English is not their first language
Biomedical Engineering <i>Fall semester admission only</i>	<b>Required</b> for all applicants/ Waived for WPI alumni and current undergraduate students	<b>Required</b> for all applicants	<b>Required</b> for all applicants	<b>Required</b> for all applicants for whom English is not their first language
School of Business	M.B.A. applicants must submit <b>GMAT</b> scores <b>GRE</b> may be substituted for M.S. and graduate certificate applicants	<b>Required</b> for all applicants	<b>Required</b> for all applicants	<b>Required</b> for all applicants whose native language is not English and who have not earned a degree from an English-instruction college or university
Chemical Engineering	<b>Required</b> for all international applicants/ <b>Recommended</b> for all others	<b>Not Required</b>	<b>Required</b> for all applicants	<b>Required</b> for all applicants for whom English is not their first language
Chemistry and Biochemistry	<b>Required</b> for all applicants/ Waived for WPI alumni and current undergraduate students	<b>Required</b> for all applicants	<b>Required</b> for all applicants	<b>Required</b> for all applicants for whom English is not their first language
Civil and Environmental Engineering	<b>Recommended</b> for all applicants	<b>Not Required</b>	<b>Required</b> for all applicants	<b>Required</b> for all applicants for whom English is not their first language
Computer Science	<b>Required</b> for all applicants/ Waived for WPI alumni and current undergraduate students; <b>Recommendation:</b> CS subject test	<b>Required</b> for all applicants	<b>Required</b> for all applicants	<b>Required</b> for all applicants for whom English is not their first language
Electrical and Computer Engineering	<b>Required</b> for all U.S. fellowship applicants/ <b>Required</b> for all international applicants	<b>Required</b> for Ph.D. applicants only	<b>Required</b> for all applicants	<b>Required</b> for all applicants for whom English is not their first language
Fire Protection Engineering	<b>Required</b> for all international applicants/ <b>Required</b> for Ph.D. applicants/ <b>Recommended</b> for all others	<b>Requested</b> for those without work experience/ <b>Required</b> for Ph.D. applicants	<b>Required</b> for all applicants	<b>Required</b> for all applicants for whom English is not their first language
Interdisciplinary MS and PH.D.	<b>See Page 78</b>			
Learning Sciences and Technology		<b>Required</b> for all applicants	<b>Required</b> for all applicants	<b>Required</b> for all applicants for whom English is not their first language
Manufacturing Engineering	<b>Required</b> for all international applicants/ <b>Recommended</b> for all others	<b>Not Required</b>	<b>Required</b> for all applicants	<b>Required</b> for all applicants for whom English is not their first language
Materials Process Engineering	<b>Required</b> for all international applicants/ <b>Recommended</b> for all others	<b>Not Required</b>	<b>Required</b> for all applicants	<b>Required</b> for all applicants for whom English is not their first language
Materials Science and Engineering	<b>Required</b> for all international applicants/ <b>Recommended</b> for all others	<b>Not Required</b>	<b>Required</b> for all applicants	<b>Required</b> for all applicants for whom English is not their first language
Mathematical Sciences	<b>GRE</b> and <b>GRE Mathematics</b> test (rescaled) <b>Recommended</b> for all applicants	<b>Not Required</b>	<b>Required</b> for all applicants	<b>Required</b> for all applicants for whom English is not their first language
Mechanical Engineering	<b>Recommended</b> for all applicants	<b>Required</b> for all applicants	<b>Required</b> for all applicants	<b>Required</b> for all applicants for whom English is not their first language
Physics	<b>Recommended</b> for all applicants	<b>Required</b> for all applicants	<b>Required</b> for all applicants	<b>Required</b> for all applicants for whom English is not their first language**
Robotics Engineering	<b>Required</b> for all applicants/ Waived for WPI alumni and current undergraduate students;	<b>Required</b> for all applicants	<b>Required</b> for all applicants	<b>Required</b> for all applicants for whom English is not their first language
Social Science/Policy Studies	<b>Not Required</b> for certificate <b>Required</b> for all other applicants	<b>Not Required</b> for certificate/ <b>Required</b> for all other applicants	<b>Not Required</b> for certificate/ <b>Required</b> for all other applicants	<b>Required</b> for all applicants for whom English is not their first language

\* See application requirements at [grad.wpi.edu](http://grad.wpi.edu) or page 12 of this catalog for exceptions.

\*\* May be waived by the department graduate coordinator after a telephone interview for applicants who have earned their BS or MS degree at a U.S. college or university.

# Financial Information

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 3.0 in courses and research work (A = 4.0).

## 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 their assignments 10 days before undergraduate classes begin in the fall, and every day the university is open during the academic year until Commencement (see Academic Calendar on the inside front cover). TAs are expected to work 20 hours per week on their assigned duties. Some departments have more stringent requirements. Consult specific departmental descriptions for details.

## 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 as well as 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.

## 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 Office of Cooperative Education), the student must be registered for nine credits. International students with F-1 visa status may apply for two types of practical training:

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

Financial assistance is also available through the WPI Financial Aid Office in the form of through the Federal Stafford Loan and Graduate PLUS loan programs. To qualify, students must be enrolled in a degree granting program or certificate on at least a half-time basis and must be a U.S. citizen or permanent resident of the United States.

Private student loans are also available for students enrolled in certificate programs or for students that are not enrolled on an at least half-time basis. Non-Citizen's may qualify for some private loans if they have a U.S. citizen as a coapplicant.

For information on loan programs contact WPI's Financial Aid Office at 508-831-5469, or at [www.wpi.edu/+finaid/Grad](http://www.wpi.edu/+finaid/Grad).

# 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

## 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 2.5, the student is removed from the program unless the department Graduate Committee intervenes.

## 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 overall 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 as soon as possible, preferably no later than one week after the start of the next regular academic semester after receiving the grade. 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 Faculty Committee for Appeal of a Grade. The Provost 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 FRC, in consultation with the Provost, will select the members of the ad hoc committee. The Chair of the FRC will convene 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 Department Chair, Program Coordinator or Departmental Graduate Coordinator from the instructor's Department will be chosen as one member of the ad hoc committee. The other two appointees to the ad hoc committee may be any other faculty member as long as there are 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, or faculty members with close research collaborations or project advising relationships with the instructor. The ad hoc committee will examine available written information on the dispute, will be available for meetings with the student, instructor, or others as it sees fit.
4. Through its inquiries and deliberations, the ad hoc committee is charged with determining whether the grade was assigned in a fair and appropriate manner, or whether clear and convincing evidence of unfair treatment such as arbitrariness, prejudice, and/or error might justify changing the grade. The ad hoc committee will make its decisions by a majority vote. If the committee concludes that the grade was assigned in a fair and appropriate manner, this decision is final and not subject to appeal. The ad hoc committee will report this conclusion in writing to the student and the instructor, and the matter will be closed.

5. If the ad hoc committee determines that compelling reasons exist for changing the grade, it will request that the instructor make the change, providing the instructor with a written explanation of its reasons. If the instructor is willing to voluntarily change the grade in view of the ad hoc committee's recommendations, he or she submits a grade change form to the Registrar, and sends copies to the ad hoc committee. Should the instructor decline to change the grade, he or she must provide a written explanation for refusing. The ad hoc faculty committee, after considering the instructor's explanation, and upon concluding that it would be unjust to allow the original grade to stand, 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 faculty 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.

# Registration Information and Procedures

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. Registration is not complete until tuition has been paid in full.

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.

## Graduate Student Classifications

- Full-time Degree Seeking
- Part-time Degree Seeking
- Graduate Certificate or Advanced Graduate Certificate
- Student on Graduate Exchange or Internship
- Nondegree Seeking/non matriculated

## Degree-Seeking Student Registration

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

Students seeking degrees not requiring a thesis are not required to maintain continuous 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.

## Audit Registration

Students primarily interested in the content of a particular course may register as auditors. Audit registration receives no credit and receives no grade. Audit registration is controlled in limited enrollment courses. Thesis and project work cannot be taken with audit registration.

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.

## Summer Semester

The Summer Session schedule will be available on the web by January of the same calendar year. Most graduate summer courses meet in the evening hours from mid-May through the end of June. Graduate Computer Science classes run through mid-July. Many graduate students work on their research during Summer Session. For information on summer registration, ([www.wpi.edu/+Summer](http://www.wpi.edu/+Summer)) call 508-831-5999.

## Transcripts

WPI will issue one transcript of record to a student without charge. Additional transcripts are issued upon receipt of a fee of \$4 per copy.

## Course Change Policies

Graduate course change (add/drop) without penalty may occur prior to the third meeting of the course. A \$100 late fee will be charged for course changes made after the 3rd course meeting and before the 4th. Course changes after the 4th course meeting will result in a grade of W (withdrawal) and will be issued until the 10th week of the term. No tuition or fees will be refunded during the withdrawal period.

Withdrawal after the 10th week must be petitioned to the Registrar's Office. Notice to the instructor or discontinuance of attendance does not constitute withdrawal. Such notice must be submitted in writing to the Registrar's Office. Incomplete grades are transitional grades and must be changed by the instructor within 12 months. If coursework is not made up by this time, the grade automatically becomes an F.

## 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 indicate in writing 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.

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.

## Tuition and Fees

### Tuition Rate

Tuition for all courses taken by graduate students is based on a \$1159 fee per credit hour for the 2010-2011 academic year.

### Audit Rate

A 50% reduced tuition rate per semester hour for the 2010-2011 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

Tuition must be paid in full at the time of registration. The following forms of payment will be accepted: check payable to WPI, American Express, MasterCard or Discover.

## Withdrawal Policies

The University makes a substantial financial commitment at the time a course is scheduled for instruction. However, students who officially withdraw from a course before the first 10 days of the semester have passed (not including weekends) will receive a refund of 100% of the tuition and fees paid, minus a \$300 penalty. No tuition and fees paid by the student will be refunded after day 10 of the semester.

## Deferred Payment Plan

A deferred payment plan is available for the fall and spring semesters. By paying a one-time fee per use, students may divide their tuition into three equal monthly payments. For specifics, call the Accounting Office at 508-831-5728.

## Health and Accident Insurance

All graduate students must be covered by health and accident insurance equivalent to that offered under the WPI Student Health and Accident Insurance Plan. Optional coverage for a spouse or dependent is available. Payment plans are available. Please contact the Accounting Office (508-831-5741) for further information.

# 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).<sup>1</sup> 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.

For the master of mathematics, the student must have a program GPA<sup>2</sup> of 2.9 or greater. For all other degrees, the student must have a program GPA of 3.0 or greater.

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 3 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 25). 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.

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.

### **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 = 3 credit hours. Graduate courses applied toward the undergraduate degree are awarded undergraduate credit with a conversion rate of 1 credit hour = 1/9 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.

# 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 ETD Approval Form is a necessary part of the submission process
2. A 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 Web Site

In order to submit theses and dissertations electronically, students must have a WPI account, obtainable online using a PIN provided by the Projects and Registrar’s Office.

Extensive information about creating and submitting ETDs is available on the ETD Web site, [www.wpi.edu/+etd](http://www.wpi.edu/+etd).

## Thesis Binding

Students and departments may wish to retain a bound paper copy of theses and dissertations. In this case, a \$10 per copy binding fee must be paid at the Accounting Office. Once the fee is paid, students can bring the receipt and the copies to Technical Services in Gordon Library to be bound.

# Student Services

## Facilities and Services

### Bookstore

The bookstore, located on the second floor of the 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 [www.wpi.bkstore.com](http://www.wpi.bkstore.com).

For more information please call (508) 831-5247 or e-mail [bkswpi@bncollege.com](mailto: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 \$300. 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](http://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 Web site. 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 Web site, 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 [www.wpi.edu/Admin/Police/parking/](http://www.wpi.edu/Admin/Police/parking/).

### Career Development Center

The Career Development Center (CDC) at WPI assists students in the development of lifelong skills related to careers and the job search process. CDC serves undergraduate and graduate students and alumni as well. Information and guidance is provided in the areas of full-time employment, graduate school, part-time employment, cooperative education and summer positions. Call 508-831-5260 or go to [www.wpi.edu/Admin/CDC/](http://www.wpi.edu/Admin/CDC/).

### 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.

## Computer Resources

WPI's Fuller Laboratories provides dedicated space for faculty, staff and students working in the information sciences.

The Academic Technology Center and Computing and Communications Center (CCC) are located in this building, along with the Computer Science Department.

The ATC serves the WPI community by supporting the electronic classrooms throughout the campus, maintaining a large inventory of audio/visual (A/V) equipment available for loan for academic presentation purposes, and providing A/V support for meetings, conferences, and special events on campus. The ATC also manages *myWPI*, the learning and information portal for members of the WPI community.

CCC provides a wide range of services and access to computer resources for the WPI community and manages an array of powerful UNIX, Linux and Windows servers. All WPI students may obtain a login ID from the CCC for academic course works, research and self-education. The login ID will remain valid as long as the person continues to be registered as a student. The systems have been configured so that the user will see the same familiar environment no matter which CCC workstation is used. CCC facilities are accessible from a wide variety of locations on campus or from around the world via the campus connection to the Internet. CCC operates the campus data network and Internet connectivity, including a VPN (Virtual Private Network) to access internal resources remotely. CCC also provides each student with personal network storage space. Computer systems operated by academic departments are also on the same CCC communications infrastructure, so they are accessible just as easily.

The CCC facilities offer high-end PCs and Macs. In addition to several computer classrooms and specialized labs, the CCC supports open access labs in every academic building totaling hundreds of stations across the campus. Each of these labs offers the same user interface, software profile, and network access to personal files as does the CCC lab. Several computer labs are available 24/7 by using a valid WPI ID card with our card access system.

Networked black & white and color laser printers as well as scanning devices are available in the CCC computer labs. Students can use the CCC print service to generate high-quality output for reports and resumes. The servers also provide file service for many software packages including spreadsheets, databases, programming languages, and department courseware.

A wireless network is available in all academic buildings as well as primary residence centers. Wireless laptops are available on loan for use in the library and campus center. In addition to supporting the academic computing system on campus, CCC operates the administrative system that provides data processing services to WPI administrative offices. The WPI information system provides ready access to important registration information. Students update their biographical information, check grades and drop/add courses over the network via the web interface to the administrative system.

CCC manages a computer help desk to answer users' questions on any of the computer platforms and to provide technical support for endorsed software packages. CCC also provides instruction sessions on supported software in the state-of-the-art computer-training classroom that the CCC maintains in the Gordon Library.

## Gordon Library

The George C. Gordon Library supports the informational and research needs of the WPI graduate community. The library staff works closely with each department to augment library resources pertinent to graduate and other research interests. The collection currently numbers approximately 271,000 books, plus an e-book collection of close to 39,000. The collection includes subscriptions to 900+ hard copy journals and approximately 35,000+ electronic titles. The collection also includes WPI electronic theses and dissertations in print and electronic formats. The WPI Archives and Special Collections hold the records and artifacts of WPI, as well as a significant number of rare books.

Many services and resources are available to graduate students 24 hours a day via the library's web site (<http://www.wpi.edu/Academics/Library>). Here students can access the library's catalog, over 150 electronic databases, full-text journal articles, online reference materials, and other resources, local and remote. Forms are available on the Web site and within Your Account in the library catalog to place interlibrary loan requests (for items not available via WPI's collections), make suggested purchase recommendations, request a research consultation, and request retrieval of items in storage. Instructional videos and course web pages provide guidance in use of the library. The library building offers a variety of work spaces for both quiet and group study, including seven Tech Suites that offer plasma screen and dedicated computer, DVD and VCR player, and network access. Web conferencing is also available in the Tech Suites.

Library staff can be contacted in person, by telephone, by e-mail, and by chat. E-mail queries can be sent through the Ask-Library-Questions form on the web. Reference staff can be phoned at 508-831-6700 and Circulation staff are available at 508-831-5410. InstantAnswers, the chat-based reference service, is available through various instant messaging applications with the screen name *wpiref*. Throughout the year, members of the reference department conduct both general interest and course-integrated instruction sessions. Orientation sessions are also offered to graduate students.

In addition to Gordon Library's resources, WPI students may utilize the collections of other Worcester area libraries. Students with a WPI ID and an ARC cross-borrowing card can borrow directly from Assumption College, Becker College, Clark University, College of the Holy Cross, Worcester State College and others. ARC cards can be obtained at the Gordon Library Circulation desk.

For more information on library services available to graduate students, please visit: <http://www.wpi.edu/Academics/Library/About/Services/graduate.html>.

## 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/](http://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 an international student population of 204 undergraduates and 209 graduate students from 65 countries (Spring semester, 2006), 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.

There are athletic facilities for tennis, swimming, bowling, squash, basketball, racquetball and volleyball, as well as a weight-lifting room, a fitness center, a sauna and several outdoor playing fields. 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 on the ground floor of Founders 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. The Dean oversees the distribution of graduate TAs, the annual graduate student orientations, and Graduate Research Achievement Day. In addition, the Dean serves as the chief academic advisor to the Graduate Student Government. Graduate students are welcome to consult with the Dean on academic matters.

## 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.

# Departments

## Programs

### Specializations

#### Course Descriptions

<b>Biology and Biotechnology</b> . . . . .	<b>28</b>
<b>Biomedical Engineering</b> . . . . .	<b>30</b>
<b>School of Business</b> . . . . .	<b>35</b>
<b>Chemical Engineering</b> . . . . .	<b>44</b>
<b>Chemistry and Biochemistry</b> . . . . .	<b>48</b>
<b>Civil and Environmental Engineering</b> . . . . .	<b>51</b>
<b>Computer and Communications Networks</b> . . . . .	<b>58</b>
<b>Computer Science</b> . . . . .	<b>60</b>
<b>Electrical and Computer Engineering</b> . . . . .	<b>66</b>
<b>Fire Protection Engineering</b> . . . . .	<b>75</b>
<b>Interdisciplinary Programs</b> . . . . .	<b>78</b>
<b>Learning Sciences and Technologies</b> . . . . .	<b>80</b>
<b>Manufacturing Engineering</b> . . . . .	<b>84</b>
<b>Materials Process Engineering</b> . . . . .	<b>87</b>
<b>Materials Science and Engineering</b> . . . . .	<b>88</b>
<b>Mathematical Sciences</b> . . . . .	<b>93</b>
<b>Mechanical Engineering</b> . . . . .	<b>103</b>
<b>Physics</b> . . . . .	<b>115</b>
<b>Robotics Engineering</b> . . . . .	<b>117</b>
<b>Social Science &amp; Policy Studies</b> . . . . .	<b>121</b>

## 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 Life Sciences and Bioengineering Center at Gateway Park. This interdisciplinary state-of-the-art building integrates Life Sciences and Bioengineering graduate programs at WPI and houses a number of technology centers, such as the Bioengineering Institute (BEI).

The Department offers a fulltime research-oriented program for incoming graduate students, leading to either a doctor of philosophy (Ph.D.) in 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 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 academic and private sectors or further graduate education.

Faculty in the Biology and Biotechnology Department have research interests in: molecular/cellular/developmental biology, regenerative medicine, plant biology, molecular ecology and evolution, applied microbial systems, and biofuels. 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 area. The department strongly recommends that, prior to applying, students review the information at the department’s Web site (<http://www.wpi.edu/Academics/Depts/Bio>) to help identify potential faculty advisors.

## Application and Admission

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

## Admission Requirements

See page 12.

## Degree Requirements

### M.S. in Biology and Biotechnology

Students pursuing the M.S. degree in biology and biotechnology must complete a minimum of 30 credit hours of course and theses work, six of which must be thesis research credits. In addition, M.S. students must successfully complete (grade of B or higher) as minimum of three graduate courses appropriate to their area of study (subject to pre-approval by their thesis committee) and the graduate seminar (BB 501, 1 credit in every semester registered for full-time study). Students must assemble an Advisory Committee of three faculty members of which a minimum of two must be biology and biotechnology program faculty members. One of the biology and biotechnology faculty members will chair the committee and be the student’s faculty advisor. The Advisory Committee must review and approve each M.S. student’s program of study and thesis research.

### Ph.D. in 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 provided to entering students.

## Publications

In order to graduate, at least one manuscript should be submitted for publication in a refereed journal and at least one paper must have been presented at a national or international conference.

## Qualifying Exam, Reports and Dissertation Defense

A Ph.D. qualifying exam is required and should be taken prior to 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.

## Faculty

**E. W. Overström**, Professor and Department Head; Ph.D., University of Massachusetts-Amherst; oocyte biology, developmental cell biology, animal somatic cell cloning.

**D. S. Adams**, Professor; Ph.D., University of Texas; design of neurotrophic factors for treating stroke, human stem cell matrices for treating spinal cord injuries.

**T. C. Crusberg**, Professor Emeritus; Ph.D., Clark University; heavy metal bioremediation, cryptobiotic desert soil crusts as indicators of environmental change.

**A. DiIorio**, Ph.D., WPI, bioprocess design technologies for overall process improvement and remediation of heavy metals from waste water using a naturally produced biopolymer.

**T. Dominko**, Associate Professor; Ph.D., University of Wisconsin-Madison; regenerative cell biology, reproductive/ developmental biology.

**J. B. Duffy**, Associate Professor; Ph.D., University of Texas; signal transduction and cell adhesion mechanisms in development and disease, cancer biology, neuronal development.

**R. J. Gegear**, Assistant Professor; Ph.D., University of Western Ontario; behavioral/evolutionary ecology, neuroethology, pollination biology.

**D. G. Gibson III**, Assistant Professor; Ph.D., Boston University; amino acid neurotransmitters, arthropod hormones and growth factors, invertebrate neuromuscular junctions.

**L. M. Mathews**, Associate Professor; Ph.D., University of Louisiana; population genetics and evolution of marine and aquatic invertebrates, design and application of molecular genetic tools for ecological research, conservation biology.

**R. L. Page**, Research Assistant Professor; Ph.D., Virginia Polytechnic Institute and State University; regenerative cell biology, somatic cell cloning.

**S. M. Politz**, Associate Professor; Ph.D., UCLA; genetic control of surface glycoprotein expression in the nematode *Caenorhabditis elegans*, chemosensory control of nematode behavior and development; host immune responses to parasitic nematode infections.

**R. Prusty Rao**, Assistant Professor; Ph.D., Penn State University Medical School; fungal pathogenesis and its regulation by small molecules, genomic screens for novel virulence factors as antifungal drug targets, genetic modification of yeast for biofuels.

**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; M.S. Biostatistics, Harvard School of Public Health; Ph.D. Genetics, Harvard University; nervous system development using *C. elegans* as a genetic model, bioinformatics approaches to understanding gene expression, computer simulations of development.

**L. Vidali**, Assistant Professor; Ph.D., University of Massachusetts-Amherst; plant cell biology and molecular genetics, live cell microscopy, molecular motors/cytoskeleton.

**P. J. Weathers**, Professor; Ph.D., Michigan State University; biology of *in vitro* cultured plants and their tissues, plant secondary metabolism, bioreactor development for plant and animal tissues, process development for plant products.

## Course Descriptions

All courses are 3 credits unless otherwise noted.

### BB 501. Seminar

1 credit per semester

### BB 515. Environmental Change: Problems and Approaches

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 560. Methods of Protein Purification and Downstream Processing

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 are 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: A knowledge of basic biochemistry is assumed.)

### BB 565. Virology

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

Specialty subject courses are offered based on the expertise of the department faculty, example topics include: Stem Cell Biology, Cell Cycle Regulation, and Model systems in Biology. Content and format varies to suit the interest and needs of the students and faculty. This course may be repeated for different topics covered. See the SUPPLEMENT section of the on-line catalog at [www.wpi.edu/+gradcat](http://www.wpi.edu/+gradcat) for descriptions of courses to be offered this academic year.

### BB 575. Advanced Genetics and Cellular Biology

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 576. Advanced Integrative Bioscience

This course concentrates on the organization of cells into biological systems and into individual organisms. Discussion will center on the development and function of specific model systems such as the nervous and immune systems. (Prerequisite: A familiarity with fundamentals of developmental biology, genetics and cell biology.)

### BB 577. Advanced Ecological and Evolutionary Bioscience

This course will explore the organization of individuals into communities, and the evolution of individual traits and behaviors. Problems discussed will range from those of population harvesting and the effect humans have on the environment to the evolution of disadvantageous traits. (Prerequisite: A familiarity with fundamentals of population interactions, evolution, and animal behavior.)

### BB 578. Advanced Applied Biology

This course examines the use of biotechnological advances toward solving real-world problems. Students will discuss problem-solving strategies from the current literature in the areas of medicine, agriculture, environmental protection/ restoration and industrial biotechnology. (Prerequisite: A familiarity with biochemistry, microbiology, and plant and animal physiology.)

### BB 598. Directed Research

### BB 599. Master's Thesis

### BB 699. Ph.D. Dissertation

## 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 in-depth 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 courses to be counted towards both degree requirements, thereby reducing total class time. With careful planning and motiva-

tion, 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 Engineering.

## 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 6 credits of life science, 6 credits of biomedical engineering, 6 credits of advanced engineering math, (including 3 credits of statistics), and 6 credits of electives (any WPI graduate-level engineering, physics, math, biomedical engineering, or equivalent course, subject to approval of the department head or the student's Academic Advisor). 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 6 credits of life science, 12 credits of biomedical engineering, 6 credits of advanced engineering math, (including 3 credits of statistics), and 9 credits of electives (any WPI graduate-level engineering, physics, math, biomedical engineering, or equivalent course, subject to approval of the department head or the student's Academic Advisor). 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:

- Biomedical Engineering (12 credits)
- Life Sciences (9 credits)
- Advanced Engineering Mathematics (3 credits)
- Statistics (3 credits)
- Laboratory Rotations (6 credits)
- Responsible Conduct of Science (1 credit)
- Advanced Courses and Electives (12 credits)
- Dissertation Research (30 credits)

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.

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 student's Academic Advisory 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 Interests 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) 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.

## 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

## Nuclear Magnetic Resonance Imaging and Spectroscopy

*Prof. Sotak*

Research projects in nuclear magnetic resonance (NMR) imaging and spectroscopy stress experimental aspects of NMR and their application in both medical and nonbiological areas. Major biological research projects include: (1) development of magnetic resonance imaging (MRI) methods for the evaluation of therapeutic interventions in acute stroke; (2) development of fluorine-19 (<sup>19</sup>F) MRI and magnetic resonance spectroscopy

(MRS) methods for measuring tumor oxygenation and evaluating adjuvants for tumor therapy; and (3) characterization of structural information in fluid-saturated porous media using diffusion imaging and spectroscopy.

## 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) constitutive modeling, (3) creation of bioartificial tissues *in vitro*, and (4) the effects of mechanical stimulation on the functional properties of cells and tissues.

## 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.

## 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.

## 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 each BME research laboratories is given below.

### 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.

### 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.

### 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-en-

gineered 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.

## Faculty

**K. H. Chon**, Professor and Department Head; Ph.D., University of Southern California; medical instrumentation for noninvasive and wireless physiological monitoring, identification and modeling of physiological systems, biomedical signal processing with applications to diabetic autonomic neuropathy, atrial fibrillation detection, blood volume loss detection, and detection of decompression sickness.

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

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

**D. Granquist-Fraser**, Ph.D., Assistant Professor; Ph.D., Boston University; Sensors and Signal Processing for Biomedical Applications and Biometry; Biomorphing Engineering for Autonomous Vehicle Visual Intelligence.

**Y. Mendelson**, Associate 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.

**R. L. Page**, Assistant Professor; Ph.D., Virginia Tech; molecular characterization and manipulation of primary human cells for applications in regenerative medicine, development of engineered in vitro culture and therapeutic cell/tissue construct delivery systems and analysis using in vivo model systems, primary cell dedifferentiation and transdifferentiation.

**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**, Assistant Professor, Ph.D., University of Washington, Seattle; Cardiovascular tissue engineering, bioreactor design, cell-based tissue repair, cell and molecular engineering, cell-derived extracellular matrix scaffolds, delivery and control of extracellular matrix genes.

**C. H. Sotak**, Professor Ph.D., Syracuse University; Magnetic resonance imaging (MRI) evaluation of therapeutic interventions in stroke, MRI and magnetic resonance spectroscopy (MRS) methods for evaluation of tumor oxygenation and response to therapy; characterization of structural information in fluid-saturated porous media using diffusion-weighted MRI/MRS.

## 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/ME/MTE 554. Composites with Biomedical and Materials Applications**

Introduction to fiber/particulate-reinforced, engineered and biologic materials. This course focuses on the elastic description and application of materials that are made up of a combination of submaterials, i.e., composites. Emphasis will be placed on the development of constitutive equations that define the mechanical behavior of a number of applications, including: biomaterial, tissue and materials science. (Prerequisites: Understanding of stress analysis and basic continuum mechanics.)

### **BME/ME 558. Biofluids and Biotransport**

The emphasis of this course is on modeling fluid flow within the cardiovascular and pulmonary systems, and the transport processes that take place in these systems. Applications include artificial heart valves, atherosclerosis, arterial impedance matching, clinical diagnosis, respiration, aerosol and particle deposition. Depending upon class interest, additional topics may include reproductive fluids, animal propulsion in air and water, and viscoelastic testing. (Prerequisite: A first course in biofluids equivalent to BME/ME 4606.)

### **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 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 582. Principles of In Vivo Nuclear Magnetic Resonance Imaging**

This course emphasizes the applications of Fourier transform nuclear magnetic resonance (FTNMR) imaging in medicine and biology. Course topics include review of the basic physical concepts of NMR (including the Bloch equations), theoretical and experimental aspects of FTNMR, theory of relaxation and relaxation mechanisms in FTNMR, instrumentation for FTNMR, basic NMR imaging techniques. (Prerequisites: Differential and integral calculus, ordinary differential equations.)

### **BME 591. Graduate Seminar**

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 595. Special Topics in Biomedical Engineering**

Topics in biomedical engineering. Presentations and discussions of the current literature in an area of biomedical engineering. See the **SUPPLEMENT** section of the on-line catalog at [www.wpi.edu/+gradcat](http://www.wpi.edu/+gradcat) for descriptions of courses to be offered in this academic year.

### **BME 596. Research Seminar**

Presentations on current biomedical engineering research.

### **BME 598. Directed Research**

### **BME 599. Master's Thesis**

### **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**

**The following biomedical engineering courses are also available for graduate credit.**

#### **BME 4011. Biomedical Signal Analysis**

Introduction to biomedical signal processing and analysis. Fundamental techniques to analyze and process signals that originate from biological sources: ECGs, EMGs, EEGs, blood pressure signals, etc. Course integrates physiological knowledge with the information useful for physiologic investigation and medical diagnosis and processing. Biomedical signal characterization, time domain analysis techniques (transfer functions, convolution, auto- and cross-correlation), frequency domain (Fourier analysis), continuous and discrete signals, deterministic and stochastic signal analysis methods. Analog and digital filtering. (Recommended background: ECE 2311, ECE 2312, BME 3011 or equivalent.) This course will be offered in 2006-2007, and in alternating years thereafter.

#### **BME 4023. Biomedical Instrumentation Design**

This course builds on the fundamental knowledge of bioinstrumentation and biosensors presented in BME 3011. Lectures and hands-on laboratory experiments cover the principles of designing, building and testing analog instruments to measure biological events. Design laboratories will include biopotential amplifiers and biosensor/bioinstrumentation systems for the measurement of physiological parameters. (Prerequisites: BME 2204 and BME 3011.) This course will be offered in 2006-2007, and in alternating years thereafter.

#### **BME 4201. Biomedical Imaging**

This course is a practical introduction to biomedical image processing using examples from various branches of medical imaging. Topics include: point operations, filtering in the image and Fourier domains, image reconstruction in computed tomography and magnetic resonance imaging, and data analysis using image segmentation. Review of linear-systems theory and the relevant principles of physics. Coursework uses examples from microscopy, computed tomography, X-ray radiography, and magnetic resonance imaging. A working knowledge of undergraduate signal analysis, and linear algebra is desirable. Facility with a high-level programming language is recommended. This course will be offered in 2006-2007, and in alternating years thereafter.

#### **BME/ME 4504. Biomechanics**

This course emphasizes the applications of mechanics to describe the material properties of living tissues. It is concerned with the description and measurements of these properties as related to their physiological functions. Emphasis on the interrelationship between biomechanics and

physiology in medicine, surgery, body injury and prosthesis. Topics covered include review of basic mechanics, stress, strain, constitutive equations and the field equations encountered in fluids, viscoelastic behavior and models of material behavior. The measurement and characterization of properties of tendons, skin, muscles and bone. Biomechanics as related to body injury and the design of prosthetic devices. (Recommended background: Differential and integral calculus, ordinary differential equations, familiarity with the concepts of mechanics, including continuum mechanics [ES 2501, ES 2502, ME 3501, MA 2051].) This course will be offered in 2011-2012, and in alternating years thereafter.

#### **BME/ME 4606. Biofluids**

This course emphasizes the applications of fluid mechanics to biological problems. The course concentrates primarily on the human circulatory and respiratory systems. Topics covered include: blood flow in the heart, arteries and veins, and microcirculation and air flow in the lungs and airways. Mass transfer across the walls of these systems is also presented. (Prerequisite: A background in continuum mechanics [ME 3501] and fluid mechanics equivalent to ME 3602 is assumed.) This course will be offered in 2010-2011, and in alternating years thereafter.

#### **BME/ME 4814. Biomedical Materials**

This course discusses various aspects pertaining to the selection, processing, testing (in vitro and in vivo) and performance of biomedical materials. The biocompatibility and surgical applicability of metallic, polymeric and ceramic implants and prosthetic devices are discussed. The physico-chemical interactions between the implant material and the physiological environment will be described. The use of biomaterials in maxillofacial, orthopedic, dental, ophthalmic and neuromuscular applications is presented. (Recommended background: BB 3101 or equivalent introduction to human anatomy, ES 2001 or equivalent introduction to materials science and engineering.)

#### **BME 4828. Biomaterial - Tissue Interactions**

This course examines the principles of materials science and cell biology underlying the design of medical devices, artificial organs, and scaffolds for tissue engineering. Molecular and cellular interactions with biomaterials are analyzed in terms of cellular processes such as matrix synthesis, degradation, and contraction. Principles of wound healing and tissue remodeling are used to study biological responses to implanted materials and devices. Case studies will be analyzed to compare tissue responses to intact, bioresorbable and bioerodible biomaterials. Additionally, this course will examine criteria for restoring physiological

function of tissue and organs, and investigate strategies to design implants and prostheses based on control of biomaterial-tissue interactions. (Prerequisites: BME 2604, BB 2550 or equivalent, ES 2001 or equivalent, PH 1120 or PH 1121.)

**The following courses in the Graduate School of Biomedical Sciences (GSBS) at the University of Massachusetts Medical School (UMMS) are appropriate for students in the biomedical engineering program and are available for graduate credit. While these are the most common courses taken by our students, many other GSBS courses not listed in this catalog may also be available for graduate credit.**

#### **Biomedical Science Core (I and II)**

Provides students with an integral foundation in the sciences basic to medicine, emphasizing contemporary topics in biological chemistry, transfer of genetic information, cellular architecture and regulation, and multicellular systems and processes. Students may take all or part of the core, in either quarter or semester format.

#### **Biomedical Sciences I (6 credits)**

Quarter I: Biochemistry (3 credits)

Quarter II: Molecular Biology and Genetics (3 credits)

#### **Biomedical Sciences II (6 credits)**

Quarter III: Cell Biology (3 credits)

Quarter IV: Systems (3 credits)

#### **Responsible Conduct of Science**

Ethics course on the responsible conduct of science. (1 credit)

#### **BME 850. Laboratory Rotation in Biomedical Engineering**

3 or 4 credits

Offered fall, spring and summer for students doing laboratory rotations on the UMMS campus. (Prerequisite: Ph.D. student in biomedical engineering.)

#### **BME 860. Preparation for Qualifying Examination**

Variable credits

#### **BME 900. Research in Biomedical Engineering and Medical Physics**

Variable credits

Equivalent to BME 699 Ph.D. Dissertation.

## Programs of Study

The interaction between business and technology drives every aspect of our Graduate Management Programs. We believe the future of management 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 management education.

WPI offers a variety of graduate management programs focusing on the intersection 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 management certificates are designed for technical and business professionals seeking focused, in-depth knowledge within a specific area of technology management. Certificates include: Information Security Management; Information Technology; Management of Technology; and Technology Marketing, and range in length from 5-6 courses. Students may also customize their own graduate management certificate program. For more information please see <http://biz.wpi.edu/Graduate/certificates.html>.

## Master of Business Administration (MBA)

WPI's MBA program features a set of ten 3-credit core courses, which are designed to develop the skills managers need to develop business opportunities, analyze and improve business performance, and to become a leader. In addition, the program includes two integrating experiences: a 3-credit course that seeks to challenge students to use the skills developed in the required core courses to make business decisions, in the context of case studies and simulations, and 3-credit project called the Graduate Qualifying project.

The required courses include the following 7 courses, which should be completed before the first integration experience:

- 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 Understanding Customers and Creating Value
- OBC 500 Group and Interpersonal Dynamics in Complex Organizations
- OIE 500 Analyzing and Designing Operations to Create Value

Following completion of these courses, students take:

- BUS 501 Integrating Business Concepts to Lead Innovation

To complete the core requirements, students must also take the following courses (which may be completed before or after BUS 501):

- 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
- Operations Management
- Process Design
- Supply Chain Management
- Technological Innovation
- Technology Marketing

In addition, students may choose a 6-credit Option for Specialization, which requires 6 additional credits in a particular functional area in combination with at least 6 credits of the free electives in the chosen area.

In addition to credit-bearing courses, non-credit modules are available to provide background in areas such as statistics and presentation skills, which students can access as-needed throughout the curriculum. It is expected that faculty teaching required courses would indicate which modules students would find helpful in the context of their course.

## **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:

- Management courses, choose 1 of the following:
  - FIN 500 Financial Information and Management
  - OBC 501 Interpersonal and Leadership Skills
- IT courses, choose 4 of the following:
  - MIS 574 Enterprise Systems
  - MIS 576 Project Management
  - MIS 579 E-Business Applications
  - MIS 581 Information Technology Policy and Strategy
  - MIS 582 Information Security Management
- Two free electives, which may include courses outside of management and a maximum of 3 credits of internship.

## **M.S. in Marketing and Technological Innovation (MSMTI)**

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 technological innovation features 6 required courses including:

- FIN 500 Financial Information and Management

- FIN 501 Economics for Managers
- OBC 500 Group and Interpersonal Dynamics in Complex Organizations
- OBC 501 Interpersonal and Leadership Skills
- MKT 500 Understanding Customers and Creating Value
- ETR 500 Entrepreneurship and Innovation

Students then select 18 credit hours of electives from the following courses:

- BUS 597 Internship
- BUS 598 Independent Study
- MIS 576 Project Management
- MIS 578 Telecommunications Management
- MIS 579 E-Business Applications
- MKT 563 Marketing of Emerging Technologies
- MKT 564 Global Technology Marketing
- MKT 566 Marketing and Electronic Commerce
- MKT 567 Integrated Marketing Communications
- MKT 568 Data Mining Business Applications
- OBC 531 Managing Organizational Change
- OBC 533 Negotiations
- OBC 535 Managing Creativity in Knowledge Intensive Organizations
- OIE 546 Managing Technological Innovation
- OIE 548 Productivity Management

## **M.S. in Operations Design and Leadership (MSODL)**

Today's business environments deal constantly with changes requiring leadership for operational solutions. The MSODL is a comprehensive Operations Management program that provides balance between service and production management, and offers the option to concentrate in either Supply Chain Management or Process Design, or to customize the degree with a broad selection of electives focusing in-depth on issues in operations management and related management areas.

MSODL students complete 4 required courses, as follows:

- OIE 500 Analyzing and Designing Operations to Create Value
- OIE 552 Modeling and Optimizing Processes

- OBC 500 Group and Interpersonal Dynamics in Complex Organizations
- OBC 501 Interpersonal and Leadership Skills or MIS 500 Innovating with Information Systems

Students then select 8 electives from the list below, or choose one of two concentration tracks, Supply Chain Management or Process Design:

- BUS 597 Internship
- MIS 571 Database Applications Development
- MIS 573 System Design and Development
- MIS 574 Enterprise Systems
- MIS 576 Project Management
- MIS 581 Information Technology Policy and Strategy
- OBC 533 Negotiations
- OBC 537 Leading Change
- OIE 541 Operations Risk Management
- OIE 544 Supply Chain Analysis and Design
- OIE 546 Managing Technological Innovation
- OIE 548 Productivity Management
- OIE 553 Global Purchasing and Logistics
- OIE 554 Global Operations Strategy
- OIE 555 Lean Process Design
- OIE 557 Service Operations Management
- OIE 558 Designing and Managing Six-Sigma Processes
- OIE 598 Independent Study

Supply Chain Management Track:

- OIE 541 Operations Risk Management
- OIE 544 Supply Chain Analysis and Design
- OIE 553 Global Purchasing and Logistics
- OIE 555 Lean Process Design
- Plus 4 elective courses (12 credit hours) from the approved list

Process Design Track:

- OIE 541 Operations Risk Management
- OIE 555 Lean Process Design
- OIE 557 Service Operations Management
- OIE 558 Designing and Managing Six-Sigma Processes
- Plus 4 elective courses (12 credit hours) from the approved list

## Combined B.S./Master's (M.B.A.) Program

This program is available to WPI undergraduate students. A separate and complete application to the M.B.A. program must be submitted. Admission to the Combined Program is determined by the faculty of the School of Business. The student should begin the curriculum planning process at the time he/she commences his/her undergraduate studies to ensure that all of the required prerequisite undergraduate courses are completed within the student's four years of undergraduate study.

It is recommended that the M.B.A. 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.

Students wishing to do a Combined B.S./M.B.A. must complete the following courses while an undergraduate, earning a B or better in each:

- ACC 1100 Financial Accounting
- FIN 2200 Financial Management
- MA 2611 Applied Statistics I
- MA 2612 Applied Statistics II
- MKT 3600 Marketing Management
- MIS 3700 Information Systems Management
- OBC 2300 Organizational Science
- OIE 3400 Production System Design
- ECON 1110 Introductory Microeconomics
- ECON 1120 Introductory Macroeconomics

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.B.A. via the Combined Program, the student must satisfy all M.B.A. degree requirements. In addition to the prerequisite undergraduate courses listed above, the student must complete the following graduate courses:

- ACC 514 Business Analysis for Technological Managers
- BUS 515 Legal and Ethical Context of Technological Organizations

- BUS 516 Graduate Qualifying Project (GQP)
- MKT 512 Creating and Implementing Strategy in Technological Organizations
- OBC 511 Interpersonal and Leadership Skills for Technological Managers
- OIE 513 Designing Processes for Technological Organizations
- And 12 elective credits (4 courses)

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

## Admission Requirements

Admission to WPI's Graduate Management Programs is competitive. Admission is granted to applicants whose academic and professional records indicate the likelihood of success in a challenging academic program, and whose career aspirations are in line with the focus of the specific degree program to which they are applying.

Applicants should have the analytic aptitude and academic preparation necessary to complete a technology-oriented management program. This includes a minimum of three semesters of college level math or two semesters of college level calculus. Applicants are also required to have an understanding of computer systems.

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 required for all MBA applicants; MS applicants may submit GRE in lieu of GMAT.

## Locations

Tailored to meet the challenges of working professionals, WPI offers full- and part-time graduate management study at our campus in Worcester, Massachusetts, as well as world-wide via our Advanced Distance Learning Network (see page 11).

## 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 (3 credits), MIS 571 (3 credits), MIS 573 (3 credits), MIS 578 (3 credits), OBC 500 (3 credits)
- **7 Electives Courses**  
1 of the following: FIN 500 (3 credits) or OBC 501 (3 credits)  
4 of the following: MIS 574 (3 credits), MIS 576 (3 credits), MIS 579 (3 credits), MIS 581 (3 credits), MIS 582 (3 credits)
- 2 free electives, which may be any graduate course at WPI and a maximum of 3 credits of internship

### For the M.S. in Marketing and Technological Innovation (MSMTI)

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

- **6 Required Courses**  
ETR 500 (3 credits), FIN 500 (3 credits), FIN 501 (3 credits), OBC 500 (3 credits), OBC 501 (3 credits), MKT 500 (3 credits)
- **6 Elective Courses** (3 credits each)  
Selected from the following:  
BUS 597, BUS 598, BUS 599, MIS 576, MIS 578, MIS 579, MKT 563, MKT 564, MKT 566, MKT 567, MKT 568, OBC 531, OBC 533, OBC 535, OIE 546, OIE 548

## For the M.S. in Operations Design and Leadership (MSODL)

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

### • 5 Required Courses

OIE 500 (3 credits), OIE 552 (3 credits), OBC 500 (3 credits), and either OBC 501 (3 credits) or MIS 500 (3 credits)

### • 8 Elective Courses (3 credits each)

Students may select 8 of the following electives, or may choose one of two concentration tracks, Supply Chain Management or Process Design: BUS 597, MIS 571, MIS 573, MIS 574, MIS 576, MIS 581, OBC 537, OBC 533, OIE 541, OIE 544, OIE 546, OIE 548, OIE 553, OIE 554, OIE 555, OIE 557, OIE 558, OIE 598

### Supply Chain Management Track:

OIE 541, OIE 544, OIE 553, OIE 555, Plus 4 elective courses from the previous list.

### Process Design Track:

OIE 541, OIE 555, OIE 557, OIE 558, Plus 4 elective courses from the previous list.

## 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, management of biotechnology, decision/risk analysis, conflict management, Latin American economic development, capacity planning, international accounting differences, strategy and new venture teams, and reengineering business education.

## The Collaborative for Entrepreneurship and Innovation

The Collaborative for Entrepreneurship and Innovation (CEI) is a program of the 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; the CEI@WPI ALL-OUT \$50K Business Plan Challenge; the WPI Venture Forum workshops,

monthly lecture and case presentation programs, radio show and newsletter; networking; a student-run entrepreneurs organization; the New England Collegiate Entrepreneurs Award; Web site administration of the Coalition for Venture Support; and, on a periodic basis, the CEI will offer conferences, workshops and seminars on topics of interest to entrepreneurs. Programs for high school outreach, social entrepreneurship, internship opportunities, business incubation, various awards, an Entrepreneurship Fair and a Consortium-wide business plan contest are in the planning stage. Please call 508-831-5075 or 5218 for more information.

## Faculty

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

**M. C. Banks**, Professor; Director, Collaborative for Entrepreneurship and Innovation; Ph.D., Virginia Tech; entrepreneurial teams, rural entrepreneurship, economic development and entrepreneurship, strategic planning in small and entrepreneurial companies, entrepreneurship in technological organizations, re-engineering business education.

**E. Danneels**, Associate Professor; Ph.D., Pennsylvania State University; growth and renewal of corporations through product innovation, nature and consequences of product innovativeness, characteristics of corporations with innovative new product programs, performance effects of innovative new product programs.

**S. Djamasbi**, Assistant 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. Gerstenfeld**, Professor; Ph.D., Massachusetts Institute of Technology; industrial engineering, innovation.

**H. Higgins**, Associate 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**, Associate Professor and Director of I.E. Program; 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.

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

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

**J. T. O'Connor**, Professor; Ph.D., University of Notre Dame; economics, finance, accounting, medical care financial and delivery systems.

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

**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.

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

**B. Tulu**, Assistant 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.

**J. Wang**, Assistant Professor; Ph.D., Lehigh University; health economics, corporate governance, applied econometrics, applied microeconomics.

**A. Zeng**, Associate 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.

**W. Zhao**, Assistant Professor; Ph.D., Temple University; corporate governance, international finance/business, financial markets/institutions

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

## 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. (Prerequisites: FIN 500 or equivalent content, or consent of instructor).

### **ACC 514. Business Analysis for Technological Managers**

4 credits

This course provides an understanding of the concepts and tools of business analysis. One major focus emphasizes how accounting information aids the planning, control, decision making and evaluation of the firm's operations, through product costing techniques, budgetary planning, control and evaluation of operations using accounting information, and analysis of how accounting information can advance a firm's goals and strategies. This course also provides an introduction to

the strategic role of financial management, analysis of company performance, the impact of major corporate decisions, the relationship among major stakeholders of the firm and cash management. (Prerequisites: ACC 501, FIN 502, FIN 508, MKT 506 and OIE 505 or equivalent content, or consent of instructor.)

### **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 help students practice integration of the concepts learned in the core courses in team based projects. 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: BUS 500, FIN 500, FIN 501, MIS 500, MKT 500, OBC 500 and OIE 500 or equivalent content, or consent of instructor).

### **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 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 prepare

a report describing his or her internship activities and will make a presentation before a committee including the Faculty Advisor and a representative from the sponsoring organization. Students are limited to one 3-credit, semester-length internship experience. The internship may not be completed at the student's place of employment. (Prerequisite: Completion of the required component of the individual student's graduate management degree program.)

### **BUS 598. Independent Study**

Directed in-depth independent study or seminar program following one or more of the core areas of management. Independent study can focus on a major problem in manufacturing, information systems, health systems, energy, government, etc. Each student must have a designated faculty advisor who must approve the subject and methodology in advance. Before registering for independent study, students should contact the director of graduate management programs.

### **BUS 599. Thesis**

6 to 9 credits

Research study at the master's level.

### **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 591. Business Basics**

This course offers an introduction to some of the theories, tools, and practices of business. The audience is non-business students, especially those in engineering and science, who want to learn the basics in preparation for more advanced work in entrepreneurship and technology commercialization. Emphasis will be placed on organizations and leadership, entrepreneurial finance, and marketing, but other aspects of business operations and strategy will be addressed, as well. Prerequisite: None. Restrictions: May not be taken for credit by students in any graduate management/business program.

### **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. (Prerequisite: ETR 591 or instructor consent.)

### **ETR 594. Technology Commercialization Project**

This course requires the student to analyze and develop an implementation proposal for actual technology commercialization projects. The students will work as multidisciplinary teams and, using a variety of tools, prepare commercial feasibility investigations; financial analysis scenarios; resource schedules; and assessments, recommendations, and justification of best pathways to market. Emphasis will be placed on realistic opportunities that might stem from the student's own ideas, review of the WPI intellectual property portfolio, local angel capital projects, and others. (Prerequisite: ETR 593.)

### **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 502. Finance**

2 credits

This course introduces students to the foundations of modern finance. The student is expected to gain an understanding of the time value of money, basic security valuation, investment criteria, capital market history, portfolio theory, and exchange rate risk. These topics are taught using a problem-oriented approach with an emphasis on conceptual understanding and the acquisition of the appropriate analytical and quantitative skills. (Prerequisites: ACC 501 or equivalent content, and a knowledge of college algebra and basic statistics.)

### **FIN 508. Economics of the Firm**

2 credits

This course covers the basic concepts of supply and demand. Various forms of business organization (e.g., corporations, partnerships) are discussed. Attention is paid to both consumer behavior (e.g., utility theory) and firm behavior (including production theory and cost analysis). Alternative market structures, including output markets (e.g., competition, monopoly) and inputs (e.g., labor, capital) are addressed. Additional topics include the government regulation of markets (e.g., antitrust laws), international trade, and public and merit goods.

### **FIN 509. Domestic and Global Economic Environment of Business**

2 credits

This course addresses the role of government in the economy, including concepts of income redistribution, taxation and stabilization. The fundamentals of aggregate demand and supply are also discussed. Topics include the concept and measurement of aggregate output and input (e.g., Gross Domestic Product [GDP]); Keynesian and post-Keynesian income determination analysis; fiscal policy (including government deficits and the public debt); monetary policy, the role of the Federal Reserve, and the banking system; economic growth; international trade and exchange rate determination.

### **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; interna-

tional investment decisions by firms and investors; and financing the global operations of firms. This course also explores the implications of increased competition from the BRICs (Brazil, Russia, India, and China) and "frontier" economies. (Prerequisites: FIN 500 or equivalent content, or consent of instructor.)

### **MIS 500. Innovating with Information**

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 and MIS 577 or equivalent content, or consent of the instructor.)

### **MIS 574. Enterprise Systems**

Companies have been replacing their legacy systems with enterprise systems designed to connect the entire organization, including suppliers and customers, in a web-enabled computing environment that provides information to all participants as needed. This course explores the managerial and technical challenges in implementing enterprise systems and managing an organization with such an interdependent, connected system. From

a technological view, students will use a commercially available enterprise system to build an understanding of the functional capabilities of such systems. From a managerial view, students will use business cases to develop an understanding of the process of implementing and using enterprise systems effectively in organizations. (Prerequisite: MIS 571 or equivalent content, or OIE 513, or consent of the instructor.)

### **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. *Note: credit will not be given for a previously taken MG 572 and the new MIS 578.*

### **MIS 579. E-Business Applications**

The course presents a survey of consumer and business-to-business electronic commerce models, systems, and technical solutions in the national and global contexts connecting individuals, businesses, governments, and other organizations to each other. It provides an introduction to e-business strategy and the development and architecture of e-business solutions and their technical components that focuses on the linkage between organizational strategy and networked information techniques. The course will cover how businesses and consumers use the Internet to exchange information and initiate transactions. Both theoretical concepts and practical skills with appropriate development tools will be addressed within the scope of the class. Students will develop a business plan and put that plan into action through development of an e-business website using commercially available development tools. Other hands-on projects and assignments are included. (Prerequisite: MIS 571 and MIS 577 or equivalent content, or consent of the instructor.) *Note: credit will not be given for a previously taken MG 572 and the new MIS 579.*

### **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. (Prerequisites: MIS507 or equivalent content, or consent of instructor.)

### **MIS 582. Information Security Management**

This course will introduce CERT-CC's five-step process for the management of information security, and is aimed at teaching managers how to create a solid enterprise-wide information security practice. This course is aimed at any student interested in gaining a managerial-level understanding of information security and practice. Readings, demos, lectures, case studies and real world events will be discussed with the intent of bridging theory with practice, law and ethics. The course is broken up into six sections: introduction to information security and architecture, hardening and security, preparation for an attack, detection of the attack, incident response, and security improvement. Additional topics covered include an overview of computer crimes, information warfare, cyber terrorism and protection of critical infrastructures. Upon completion of this course, the student will have an in-depth understanding of the steps required to build and maintain an information security department, and the depth of technical understanding to be able to communicate effectively with information security teams.

### **MKT 500. Understanding Customers and Creating Value**

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 512. Creating and Implementing Strategy in Technological Organizations**

This course focuses on understanding the market and the importance of market research, customer needs, competitor analysis, business environment and forecasting. The development of ethical and effective strategy is discussed, including exploiting and developing the core competencies of the organization. Promoting and developing interfunctional and international communication and cooperation are addressed. Special attention is paid to the integration of emerging technologies. Other areas covered include assessment analysis, including controlling quality and tracking customer response. (Prerequisite: MKT 506 or equivalent content, or consent of the instructor.)

### **MKT 563. Marketing of Emerging Technologies**

This course focuses on the new product development process in high-tech corporations, from idea generation through launch. Topics include: understanding customer responses to innovation, engaging customers in the innovation process, developing the marketing mix for new products (product features and benefits, pricing, channel selection, communications), new product introduction timing and competitive positioning. Particular emphasis is placed on how new products can be used to generate firm growth and renewal in a dynamic environment, and on the challenges of incorporating emerging technologies in new products. (Prerequisite: MKT 506 or equivalent content, or consent of the 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. *This course is offered by special arrangement only, based on expressed student interest.*

### **MKT 566. Marketing and Electronic Commerce**

This course discusses the tools and techniques being used today to harness the vast marketing potential of the Internet. It examines various Web-based business models for effectively and efficiently using the net as a strategic marketing tool for new products, market research, direct and indirect distribution channels, and marketing communications. The course considers both business-to-consumer and business-to-business applications, and explores the major opportunities, limitations and issues of profiting from the Internet.

### **MKT 567. Integrated Marketing Communications (IMC)**

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.

### **OBC 500. Group and Interpersonal Dynamics in Complex**

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**

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. (Prerequisites: OBC 500 or equivalent content, or consent of instructor.)

### **OBC 533. Negotiations**

This course focuses on improving the student's 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. (Prerequisites: OBC 500 or equivalent content, or consent of instructor.)

### **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. (Prerequisites: OBC 500 or equivalent content, or consent of instructor.)

### **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 513. Designing Processes for Technological Organizations**

This course introduces students to the critical role of processes in modern technological organizations. This course addresses organizational, technical and ethical issues related to designing, analyzing and reengineering business processes. Techniques and tools for process design are covered. Key global processes such as customer service, order fulfillment, and goods/services creation and distribution processes and their enabling information technology are studied in detail. (Prerequisites: MIS 507, OBC 503 and OIE 504 or equivalent content, or consent of instructor.)

### **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. (Prerequisites: OIE 504, or equivalent content, or consent of instructor.)

### **OIE 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.

**OIE 548. Productivity Management**

This highly interactive course focuses on evaluating and measuring productivity in both manufacturing and service environments, and on selecting, planning, and implementing measures to maximize it. Overall strategies as well as specific techniques are studied. The course examines key productivity drivers such as new and historical approaches to management, employee motivation/reward systems, the role of technology as both a production environments, business process reengineering, the role of communications, the impact of capital spending, and cutting edge thinking on operations structuring and execution.

**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. *This course is offered by special arrangement only, based on expressed student interest.*

**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.

## 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.

#### 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.

### 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.

## Research Interests

The Chemical Engineering Department's research effort is concentrated in the following major areas: nanotechnology/nanomaterials, environmental engineering, energy research, bioengineering, process control and safety, and reaction engineering.

Bioengineering research in the department focuses on biomaterials, cell-surface interactions, development of DNA-based biosensors, and modeling of HIV interactions with the immune system. Environmental Engineering encompasses air pollution and pollution prevention in chemical processes, environmentally benign chemical reactor technology, fuel cell technology, and molecular modeling of catalyst materials. Process control involves analysis and control of nonlinear processes. Master's and doctoral candidates' research in these areas involves the application of all fundamental aspects of chemical engineering, as well as interdisciplinary projects that encompass environmental engineering and science, biomedical engineering, materials science, and math.

Of the 20 to 25 graduate students, approximately 75% are Ph.D. candidates. Research groups tend to be small; because of this, students find considerable interaction with faculty advisors as well as among various research groups. In such an atmosphere, graduate students have exceptional opportunities to contribute to their field. Studies may be pursued in the following areas:

## Nanomaterials

### 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. Projects include diffusion through porous solids, multicomponent adsorption, mechanism studies; microkinetics, synthesis and characterization of catalysts; catalytic reformers; heat and mass transfer in catalytic reactors; and reactor dynamics.

### Zeolite Science and Technology

Research in the area of zeolite science involves synthesis, characterization and applications of molecular sieve zeolites. In particular, developing an understanding of 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.

## Biological Engineering

### Bioseparations

Full realization of biotechnology's potential to produce useful products will require the engineering of efficient and, in some cases, large-scale production and recovery processes. Research in the bioseparations laboratory is aimed at understanding and exploiting the thermodynamic and transport properties of biological materials such as genetic materials underlying their separation, to improve existing purification methods and develop new separation techniques. Recent projects include partitioning in aqueous two-phase systems, affinity partitioning, extractive fermentation, filtration using inorganic membranes, and a new large-scale electrophoretic separation method.

### 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-domain 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 of interest.

### **Bacterial Adhesion to Biomaterials**

The mechanisms governing bacterial adhesion to biomaterials, including catheters and other implanted devices, are poorly understood at this time. 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. Often, removal of the device is the only option since microbes attached to a surface are highly resistant to antibiotics. Work in our laboratory 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.

### **Process Analysis, Performance Monitoring, Control and Safety**

Current research efforts lie in the broader areas of nonlinear process analysis, performance monitoring, control and safety. In particular, the following thematic areas may be identified in our current research plan: (1) synthesis of robust optimal digital feedback regulators for nonlinear processes in the presence of model uncertainty; (2) design of state estimators for digital process performance monitoring and fault detection/ diagnosis purposes; (3) chemical risk assessment and management with applications to process safety; (4) development of the appropriate software tools for the effective digital implementation of the above process control, monitoring and risk assessment schemes.

### **Environmental and Sustainable Engineering**

#### **Bacterial and Biopolymer Interactions in the Aquatic Environment**

Our interests are directed to identifying the roles bacteria and bacterial extracellular polymers play in environmental processes. Experimental work is focused on characterizing biocolloid systems at the nanoscale. The main areas of interest

are in studying the nanoscale interactions between bacterial surface molecules and natural organic materials in the environment. Applications of this work involve natural and engineered systems, and include improving in situ bioremediation efforts, prevention of water contamination with pathogenic microbes, and the design of better treatment options for wastewater.

### **Air & Water Remediation**

Research is being carried out to evaluate the use of hydrophobic molecular sieves to clean air and water contaminated with organic compounds. Benefits of using hydrophobic molecular sieves have been demonstrated, and our investigations in the laboratory have been confirmed by Molecular Dynamics calculations as well as equilibrium calculations using an equation of state for fluids confined in nano-meter sized pores.

### **Hydrogen Fuel**

Hydrogen may be the energy currency of the future due to environmental benefits and potential use of fuel cells. Palladium and palladium alloy membranes and membrane reactors are being developed that produce pure hydrogen in a single step, simplifying the multi-step reforming processes that require additional separation processes to produce pure hydrogen.

### **Fuel Cell Technology**

Fuel cells have potential as clean and efficient power sources for automobiles and stationary appliances. Research is being conducted on developing, characterizing and modeling of fuel cells that are robust for these consumer applications. This includes development of CO-tolerant anodes, higher temperature proton-exchange membranes and direct methanol fuel cells. In addition, reformers are being investigated to produce hydrogen from liquid fuels.

### **Molecular Modeling of Catalytic Reactions**

Computer technologies have advanced to the point of being able to simulate chemical reactions and transformations with molecular detail and high accuracy. This is useful for catalytic processes which may involve a number of reactions that are difficult to determine using experimental techniques. Research is being conducted in the areas of photocatalysis, industrial catalysis, and environmental catalysis, all

with the goal of producing environmentally-safe energy and chemicals. Several types of materials are studied, including metals, metal oxides, and zeolites.

## **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 nanomaterials 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, Nicolet Magna-IR 560 FTIR with DRIFT cell for catalyst surface characterization, Rosemount Chemiluminescence NO/NO<sub>x</sub> 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<sup>2</sup> and a 25 cm<sup>2</sup> 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 applica-

tions; (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.

## Faculty

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

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

**W. M. Clark**, Associate Professor; 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**, Assistant Professor; Ph.D., Purdue University. Energy production, nanomaterials research and development, pollution control and abatement, catalysis and chemical kinetics, and computational chemistry

**A. G. Dixon**, Professor; Ph.D., University of Edinburgh. Transport in chemical reactions, applications of CFD to catalyst and reactor design, microreactors

**N. K. Kazantzis**, Associate Professor; Ph.D., University of Michigan. Analysis, sustainable design and control of chemical processes, environmental and energy systems, process safety and chemical risk analysis, process performance monitoring and industrial risks

**Y. H. Ma**, Professor; Ph.D. Massachusetts Institute of Technology. Synthesis, characterization, and application of inorganic membranes, including composite Pd and Pd-alloy porous stainless steel membranes for hydrogen separation

**R. W. Thompson**, Professor; Ph.D., Iowa State University. Applied kinetics and reactor analysis, especially as applied to the analysis of particulate systems

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

### Emeritus

**W. R. Moser**, Professor Emeritus; Ph.D., Massachusetts Institute of Technology

**R. E. Wagner**, Professor Emeritus; Ph.D., Princeton University

**A.H. Weiss**, Professor Emeritus; Ph.D., University of Pennsylvania

## 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 background 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 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. See the SUPPLEMENT section of the on-line catalog at [www.wpi.edu/+gradcat](http://www.wpi.edu/+gradcat) for descriptions of courses to be offered in this academic year.

### CHE 594/FPE 574. Process Safety Management

This course provides basic skills in state-of-the-art process safety management and hazard analysis techniques including hazard and operability studies (HAZOP), logic trees, failure modes and effects analysis (FMEA) and consequence analysis. Both qualitative and quantitative evaluation methods will be utilized. Following a case study format, these techniques, along with current regulatory requirements, will be applied through class projects addressing environmental health, industrial hygiene, hazardous materials, and fire or explosion hazard scenarios. (Prerequisite: An undergraduate engineering or physical science background.)

## 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.

## 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.

Each student should select a research advisor no later than the end of the first term (seven weeks) of residence, and research should be started by the beginning of the second term.

## For the M.S.

### Thesis

The M.S. degree in chemistry or biochemistry requires 30 semester hours of credit, of which at least 6 or more must be thesis research, and the remainder in approved independent studies and courses at the 4000 or 500 level. Special requirements of the Chemistry and Biochemistry Department are that an M.S. candidate must submit a thesis based upon research conducted under the direction of a faculty member during his or her tenure at WPI. The thesis must be approved by the faculty advisor and the chairman of the Chemistry and Biochemistry Department.

## For the Ph.D.

At the end of the first semester of the second year of residence, the student must submit a written and an oral progress report on completed research to the Chemistry and Biochemistry Department. A committee of three faculty members, including the Research Advisor, will consider this progress report and the student's performance in courses, and will recommend to the department whether or not the student should complete an M.S. degree, or if the student should be allowed to continue toward a Ph.D.

### Qualifying Examination

Before formal admission to the doctoral program, Ph.D. candidates must take the qualifying examination in their field of specialization.

### Dissertation

For the final Ph.D. degree requirement the candidate must submit and defend a satisfactory dissertation to a committee of three or more, two of whom must be from the degree granting program and one of whom must be from outside the program. The dissertation must include a significant proposal for future research in the general area of his/her research.

## 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, plant pathogen interactions, enzyme structure and function, and others.
- Molecular Design and Synthesis. Within this area there is active research on topics encompassing organic synthesis and medicinal chemistry, supramolecular materials, photovoltaic materials, polymorphism in pharmaceutical drugs, spectroscopy and photophysical properties of molecules, host-guest chemistry, and more.

- Nanotechnology. 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.

## 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 (thermogravimetric analysis), polarizing optical stereomicroscope, FT-IR, UV-VIS absorption, fluorescence and phosphorescence spectroscopy; powder and single crystal x-ray diffractometers, cyclic voltammetry, impedance spectroscopy, ellipsometer, quartz crystal microbalance, grazing incidence IR, atomic force microscopic (AFM), and other surface-related facilities. Additional equipment in the biochemistry area include: centrifuges, ultra-centrifuges, 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.

## Faculty

**K. K. Wobbe**, Associate Professor and Department Head; Ph.D., Harvard University; plant pathogen interactions, viral suppression of host defenses, regulation of terpene biosynthetic genes, plant metabolic engineering.

**J. M. Argüello**, Professor; Ph.D., Universidad Nacional de Río Cuarto, Argentina; transmembrane ion transport, metal-ATPases structure-function, plant heavy metal homeostasis, thermophilic membrane protein structure and stability.

**R. E. Connors**, Professor; Ph.D., Northeastern University; photochemistry, spectroscopy, time-resolved fluorescence, photocatalysis, molecular modeling, singlet oxygen production and storage.

**R. E. Dempski**, Assistant Professor; Ph.D., Massachusetts Institute of Technology; structure-function of membrane proteins in situ, fluorescence resonance energy transfer, biochemical and biophysical approaches to ion transport.

**J. P. Dittami**, Professor; Ph.D., Rensselaer Polytechnic Institute; medicinal chemistry, organic synthesis, new synthetic methods development.

**G. A. Kaminski**, Associate Professor; Ph.D., Yale University; computational biochemistry and biophysics, complex formation, protein structure determination, protein-ligand interactions, computer-aided drug design.

**J. MacDonald**, Associate Professor; Ph.D., University of Minnesota; porous crystalline materials composed of organic & coordination compounds, polymorphism of pharmaceutical drugs, crystallization of proteins, supramolecular assembly on surfaces.

**W. G. McGimpsey**, Professor; Ph.D., Queen's University, Canada; chemical and biological sensors, chemical surface modification, thin film devices, photovoltaics, microfluidics, nanofluidics, biofilms, biocompatible surfaces.

**A. A. Scala**, Professor; Ph.D., Polytechnic Institute of Brooklyn; reactivity-selectivity relationships; thermodynamic vs. kinetic control of products; Bell-Evans-Polanyi Principle and Hammond's Postulate; transition state diagrams.

## 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

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

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 background 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. See the SUPPLEMENT section of the on-line catalog at [www.wpi.edu/+gradcat](http://www.wpi.edu/+gradcat) for descriptions of courses to be offered in this academic year.

### 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. See the SUPPLEMENT section of the on-line catalog at [www.wpi.edu/+gradcat](http://www.wpi.edu/+gradcat) for descriptions of courses to be offered in this academic year.

### 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

0.5 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 2004-2005 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 catalysis by metal complexes. (Recommended background: CH 2310 and CH 2320, or equivalent.) This course will be offered in 2002-2003 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 2005-2006 and in alternate years thereafter.

## 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 study is 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, from 4000-level undergraduate courses suitable for graduate credit, 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. 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 52).

The structural engineering research topics in the recent past at WPI are as follows – three-dimensional dynamic response of tall buildings to stochastic winds; the inelastic dynamic response of tall buildings to earthquakes; response of braced, framed-tube and outrigger-braced tall buildings to wind; dynamic response of tall buildings with base-isolation to seismic loads; eccentrically braced tall buildings to resist earthquakes; approximate methods of analysis and preliminary design of tall buildings; knowledge-based systems and neural networks for tall building design; 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; contaminant transport, transformation and modeling; 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, biological wastewater treatment, environmental fluid dynamics and coastal processes, contaminant fate and transport in groundwater and surface water, exchanges between surface and subsurface waters, computer simulations of distribution systems, and land use development and controls.

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 585 and FIN 500. (FIN 500 can be substituted by an equivalent 3-credit-hour course approved by 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.

### Highway Infrastructure

The objective of the highway infrastructure program is to provide a center for learning and education for the engineers who will design, build and maintain tomorrow's highway infrastructure.

The highway infrastructure program is a multidisciplinary interdepartmental program designed to prepare students for careers designing, maintaining and managing highway infrastructure systems. Students

gain proficiency in highway infrastructure technology 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 highway infrastructure 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 Iowa 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 highway infrastructure program include developing side-impact crash test and evaluation procedures, developing procedures for performing in-service performance evaluations of traffic barriers, assessing the field performance of traffic barriers, finite element analysis of crash events, structural crash-worthiness, 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.**

A B.S. degree in civil engineering (or another acceptable engineering field) is required for admission to the M.S. program in civil engineering. Students who do not have an ABET accredited B.S. degree may wish to enroll in the interdisciplinary 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. 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 585 Information Technology in the Integration of Civil Engineering), 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 three civil and environmental engineering laboratories (Environmental Lab, Geotechnical Lab, and Materials/Structural Lab), plus three computer laboratories located within Kaven Hall, as well as a structural mechanics impact laboratory. 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.

### **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, and
- A large-mass drop tower.

## **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 atomic absorption spectrophotometer, 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.

## **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.

## **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.

## 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, water quality testing probes, and a variety of equipment for hydrologic monitoring and water quality testing.

## Computer Laboratories

The CEE Department has a number of computer laboratories that are located in Kaven Hall and connected to WPI's network, including two large laboratories that are available for general student use. One of these laboratories includes 28 Dell Optiplex Core 2 Duo Computers, operating at 2.66 Gigahertz on Windows Vista. The other laboratory (known as the AutoCAD Lab, which is 2000 feet in area) contains 23 Dell Optiplex 745 Core 2 Duo Computers, also operating on Windows Vista. In addition, hook-up jacks to network connections for laptop computers are provided at four large group tables in the center of the room. A complete presentation system (computer projector, VCR and sound system) is housed in this facility. Primary use of this laboratory is for courses and civil engineering group project work.

## 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.

**W. V. Collentro**, Adjunct Assistant Professor; M.S., Worcester Polytechnic Institute

**F. L. Hart**, Professor; Ph.D., University of Connecticut; water quality changes in distribution systems, tracer analysis of reactors, water quality changes in wet pipe fire sprinklers.

**P. Jayachandran**, Associate Professor; Ph.D., University of Wisconsin; tall buildings, design.

**M. Kearns**, Adjunct Instructor; M.S., Worcester Polytechnic Institute

**Y. Kim**, Assistant Professor; Ph.D., Texas A&M University; control theory and applications, modeling of complex systems, fuzzy logic theory and applications

**R. B. Mallick**, Associate Professor; 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.

**B. J. O'Rourke**, Adjunct Instructor; J.D., Boston College, M.S., Cornell University

**J. C. O'Shaughnessy**, Professor; Ph.D., Pennsylvania State University; sustainability and green engineering, industrial waste/pollution prevention; hazardous waste destruction.

**R. Pietroforte**, Associate Professor; Ph.D., Massachusetts Institute of Technology; construction management, construction economics, architectural engineering.

**J. D. Plummer**, Associate Professor and Schweber Professorship in Environmental Engineering; Ph.D., University of Massachusetts, Amherst; surface water quality, microbial source tracking, alternative disinfection strategies.

**M. H. Ray**, Professor and White Chair; Ph.D., Vanderbilt University; impact mechanics, transportation safety, structural mechanics.

**G. F. Salazar**, Associate Professor; Ph.D., Massachusetts Institute of Technology; integration of design and construction, models and information technology, cooperative agreements.

**Mingjiang Tao**, Assistant Professor; Ph.D., Case Western Reserve University; soil mechanics, geotechnical-pavement engineering, geo-material characterization and modeling.

**T. J. Vadney**, Adjunct Instructor; M.B.A., Southern New Hampshire University

## 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. *This course is offered by special arrangement only, based on expressed student interest.*

### **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 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 527/ME 5327. Impact Strength of Materials**

This course provides the student with a basic understanding of the mechanics of impact and contact as well as the behavior of materials subjected to dynamic loadings. Topics will include elastic and plastic stress waves in rods; longitudinal, torsional and flexure waves; shock waves; impulsively loaded beams and plates; impact of rough bodies in three dimensions, impact of bodies with compliance, impact of slender deformable rods, continuum modeling of contact regions and progressive collapse of structures.

### **CE 529/ME 5329. Impact Finite Element Analysis**

Modern practical contact/impact problems like the design of automobiles, aircraft, ships, packaging, etc. depend on the use of nonlinear dynamic large-deformation high-strain rate explicit finite element computer programs. The purpose of this course is to provide the student with background sufficient for them to understand the workings of such programs and the ability to use such programs to build models and perform analyses of contact/impact problems. Topics will include explicit time integration, penalty and constraint contact methods, under-integrated element formulations, hourglass control, developing finite element models and performing and interpreting finite element analysis results.

### **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 will provide a detailed survey of analysis and design concepts for flexible and rigid pavements for highways and airports. The materials will cover 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 will be presented. A review of pavement rehabilitation methods and processes will be 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 543. Highway Design and Traffic Safety**

This course is an in-depth study of highway safety as it affects the geometric design of highways. Topics include the classification and purposes of roadway systems, developing safety design criteria, the design of safe vertical and horizontal alignments, proper selection of cross-sectional elements, providing adequate sight distance, selection of appropriate speed limits, control of speeds, and other highway design issues. While there is no formal prerequisite, the course presumes a basic knowledge of undergraduate highway design as taught in CE 3050. This course is usually offered in alternate spring semesters.

### **CE 553. Advanced Foundation Engineering**

This course covers advanced methods of subsurface exploration and recent developments in prediction of bearing capacity and settlement of shallow foundations. It includes design of mat foundations, analysis and design of pile and drilled shaft foundations, and discussion of case studies. The course content is determined in part by the student's interests and often also includes design of lateral support systems, reinforced earth, dewatering systems and buried structures.

### **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 562.1. 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. Stream, Lake and Estuarine Analysis**

This course provides a quantitative base for determining the fate of effluent discharged into natural waters. Models are developed to describe the transport, dispersal, and chemical/biological reaction of substances introduced in rivers, estuaries, lakes and coastal areas. The concept of conservation of mass is used to derive the general transport equation. This equation is applied to analyze BOD, DO, temperature, nutrients and plankton population dynamics. Fate of toxic pollutants is also addressed.

### **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. Multiphase Contaminant Transport**

Introduces concepts of transport processes in the environment with emphasis on exchanges across phase boundaries. Topics include equilibrium conditions of environmental interfaces; partitioning and distribution of contaminants in the environment; transport in surface water; dispersion, sorption and the movement of nonaqueous phase liquids in groundwater; exchanges across air-water interfaces; and the effects of reactions on the transport in the environment. (Prerequisite: A knowledge of the material covered in ES 3004 is expected.)

### **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 3021, CE 3023, or equivalent.)

### **CE 581. Real Estate Development**

Principles of real estate development, emphasizing the system approach to the process of conception, design, construction and operation; organization and control systems for real estate development, value and decision analysis.

### **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, CE 584 and CE 585 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 585. Information Technology in the Integration of Civil Engineering**

This course provides an understanding and hands-on experience of state-of-the-art information technology and its application to the planning, design, construction and management of civil engineering projects. These technologies include integrated database management systems, electronic data interchange (EDI), electronic media for data input/output (bar coding, voice recognition, image processing), networks and knowledge-based systems. The course format includes formal lectures, computer laboratory sessions and a class

project developed collaboratively by the students throughout the term. Using information technology, the class develops a package that includes drawings, specifications, cost estimate and schedule of a civil engineering project. (Prerequisites: basic knowledge of computers and construction project management.)

### **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. (Prerequisite: CE 3023, or equivalent.)

### **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.

# Computer and Communications Networks

## Program of Study

A specialization in computer and communications networks 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 and Communications Networks (CCN)." The program is focused on preparing students for professional positions in industry, but the education also provides excellent preparation for Ph.D. study in networks.

This program prepares graduates for technical leadership positions in the design and implementation of computer and communications networks, including local- and wide-area computer networking, distributed computation, telecommunications (including voice, data and video services), wireless networking and personal mobile communications. All of the fundamental hardware and software aspects of networks will be treated in the program:

1. The seven layers of the ISO network model
2. Transmission media and terminals (including fiber optics, cable and radio)
3. Switching and routing methods (including packet switching)
4. Systems modeling and performance analysis
5. Methods of distributed computation
6. Current and evolving standards and protocols
7. Impacts of the information type (voice, video, text, etc.) on optimal transmission and routing methods

An accelerated part-time option is available with cooperating corporations, with program completion possible in two years.

## CCN Project

Each student in the CCN specialization must complete an in-depth project demonstrating the ability to apply and extend the material studied in their coursework. Students have the option of completing a practice-oriented internship or a research-oriented thesis.

The internship is a high-level network engineering experience, tailored to the specific interests and background of the student. Each internship is carried out in cooperation with a sponsoring organization, and must be approved and advised by a WPI faculty member in the CS department. Internships may be proposed by a faculty member, by an offcampus sponsor or by the student. The internship must include proposal, design and documentation phases, and generally includes implementation and testing. The student will prepare a report describing the internship activities, and will make a presentation before a committee including the faculty advisor and a representative of the sponsoring organization. Internship examples include transceiver design for new media, security and encryption protocols, protocol converters, databases to support efficient routing, and network system designs.

The thesis option for the CCN project is a research-oriented experience in an area of current research in an area of computer and communications networks. The thesis must be pursued under the direction of a WPI faculty member in the CS department. The result of the thesis is a thesis document, describing the results of the research, and a public presentation.

## 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. Admission is highly selective and decisions will be based both on previous academic performance and on relevant technical experience. Admission decisions are made by the CS department.

## Degree Requirements

33 credits

### Required Courses

(4 courses, 12 credits):

- Analysis of Probabilistic Signals and Systems or Analysis of Computations and Systems (ECE 502, CS 504, or CS 524)
- Introduction to Local- and Wide-Area Networks (CS 513)

### and two of the following courses:

- Telecommunications Transmission Technologies (ECE 535)
- High Performance Networks (CS 530)
- Advanced Computer and Communications Networks (CS 577)
- Modeling and Performance Evaluation of Networks and Computer Systems (CS 533)

## Elective Courses

(at least three from list):

- Digital Communications: Modulation and Coding (ECE 532)
- Advances in Digital Communication (ECE 533)
- Multiple Processor and Distributed Systems (CS 515)
- Advanced Operating System Theory (CS 535)
- Design of Software Systems (CS 509)
- Multimedia Networking (CS 529)
- Wireless Information Networks (ECE 538)
- Cryptography and Data Security (CS 578)
- Advanced Cryptography (ECE 579R)
- Telecommunication Policy (ECE 508)
- Mobile Data Networking (ECE 539S)
- Any of the courses ECE 535, CS 530, CS 577, and CS 533 not taken to satisfy the required courses above.

## CCN Project

The student must complete one of the following:

1. Computer and Communications Networks Internship (CS 595) (6 credits)  
This project requirement may be waived with documentation of relevant industrial experience. The waiver must be approved by the CS Graduate Program Committee in consultation with the CCN director. If this requirement is waived, the student must take two additional courses from the list of elective courses above, or two additional courses approved by the department's Graduate Program Committee.
2. Master's thesis in the area of computer and communications networks (9 credits)

## Free Electives

Free electives may be used to bring the total to 33 credits. Courses may be chosen from relevant graduate-level courses in computer science, electrical and computer engineering, mathematics or management. Some students will need to use these electives to satisfy the area requirements for the CS master's degree core.

## Important Note

Since the CCN specialization is a specialization in the master's programs of the Computer Science Department, students in the CCN specialization must also satisfy all requirements of the computer science master's program. While ECE courses may be used to satisfy some of the CCN requirements, there is a limit to the number of courses outside of Computer Science that students may apply towards their Computer Science master's degree.

## 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 <http://www.cs.wpi.edu/Graduate/certificates.html>.

## BS/MS Program

### Overview

The university rules for the BS/MS program are described on page 7.

Students enrolled in the BS/MS program may count certain courses towards both their undergraduate and graduate degrees. The Undergraduate Catalog states that for the BS/MS the conversion equivalence is:

- 1/3 WPI undergraduate unit = 3 WPI graduate credit hours

*(One undergraduate course maps to one graduate course.)*

**Note:** 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. This means that only four courses can be shared between the BS and MS degrees.

The Regulations section (below) details which courses may be shared between the two degrees.

### Process

Students should apply for admission to the BS/MS program during or after taking their second 4000-level Computer Science course. In order to receive BS/MS credit for a course, the student must complete a

Course Selection Form; the instructor will indicate the conditions the student must satisfy in order to receive BS/MS credit for the course, such as earning a specific grade or doing additional assigned work.

## Regulations

The CS department allows only selected 4000-level undergraduate courses to count towards the MS degree. The 4000-level courses that may be counted towards both degrees are:

- CS 4120 Analysis of Algorithms
- CS 4123 Theory of Computation
- CS 4233 Object-Oriented Analysis and Design
- CS 4241 Webware: Computational Technology for Network Information Systems
- CS 4341 Introduction to Artificial Intelligence
- CS 4432 Database Systems II
- CS 4445 Data Mining and Knowledge Discovery in Databases
- CS 4513 Distributed Computing Systems
- CS 4515 Computer Architecture
- CS 4516 Advanced Computer Networks
- CS 4533 Techniques of Programming Language Translation
- CS 4536 Programming Languages
- CS 4731 Computer Graphics
- CS 4732 Computer Animation
- Undergraduate Independent Studies, with permission of instructor and either the Graduate Committee or the Department Chair
- CS graduate courses except CS 505

Certain pairs of undergraduate and graduate courses cover similar material. In most cases, students may not receive credit for both the undergraduate and graduate versions of the same course. Exceptions arise when the graduate course covers extensive material beyond the undergraduate course. The table below summarizes the restrictions on credit for similar courses across the undergraduate and graduate programs.

Undergraduate Course	Credit Not Also Allowed for Graduate Course	Credit Not Allowed for Undergraduate Course if You Previously Took
CS 4120 Analysis of Algorithms		CS 504
CS 4341 Introduction to Artificial Intelligence	CS 534	CS 534
CS 4432 Database Systems II	CS 542	CS 542
CS 4513 Distributed Computing Systems	CS 502	CS 502
CS 4516 Advanced Computer Networks	CS 513	CS 513
CS 4533 Techniques of Programming Language Translation		CS 544
CS 4536 Programming Language	CS 536	CS 536
CS 4731 Computer Graphics	CS 543	CS 543

Undergraduate courses listed in table above are viewed as mapping to the graduate courses listed in the third column. If an undergraduate course maps to a graduate course that satisfies a bin requirement for the MS degree, the undergraduate course satisfies that bin requirement. For example, a BS/MS student can satisfy the systems bin requirement for the MS by taking CS 4513.

## Degree Requirements For the M.S.

These degree requirements are effective for all students matriculating after November 1, 2006. Those students who matriculated prior to this date may choose to use the degree requirements stated in the graduate catalog effective at the time of matriculation. The student may choose between two options to obtain the master's degree: thesis or coursework. 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.

### M.S. Breadth Requirement

All M.S. students must complete the Breadth Requirement. M.S. students are required to achieve a passing grade in courses from four different bins, as listed below. Those four bins must include the three essential bins; the essential bins are Theory, Algorithms, and either Systems or Networks. The other bins are Design, Compilers/Languages, Graphics/Imaging, AI, and Databases.

Courses with a 5000 number (e.g., 5003, 5084) are preparatory courses, designed specifically for students with insufficient background knowledge or skills. Gradu-

ate credit can be earned for these courses 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.

#### The Bins

The following list shows the M.S. bins and the courses in them. Courses listed in multiple bins may only be used to satisfy the requirements of one bin.

**Theory:** 5003 (Intro. Theory), 503 (Found.), 521 (Logic), 559 (Adv. Th.)

**Algorithms:** 5084 (Intro. Algorithms), 504 (Analysis), 584 (Algs)

**Systems:** 502 (OS), 533 (Perf. Eval.), 535 (Adv. OS)

**Networks:** 513 (Intro LAN/WAN), 529 (Multi. Net.), 530 (HP Net.), 577 (Adv. Net.)

**Design:** 509 (SE), 546 (HCI), 562 (Adv. SE)

**Compilers/Languages:** 536 (Langs.), 544 (Compilers)

**Graphics/Imaging:** 543 (Graph.), 545 (Im. Proc.), 549 [Vision], 563 (Adv. Gr.)

**AI:** 534 (AI), 538 (Ex. Sys.), 539 (Learning), 540 (AI Design), 549 [Vision]

**Databases:** 542 (DB), 561 (Adv. DB)

For each bin, a bin committee is responsible for the administration of requirements related to that bin. These responsibilities include: recommending courses to be added or removed from their bin; determining which independent studies and special topics courses should be included in their bin; and deciding on student petitions concerning their bin. Further regulations regarding the Breadth Requirement are posted in the Graduate Regulations on the CS Department Web site <http://www.cs.wpi.edu/Graduate/guide.html>.

Please note that the Breadth Requirement for the Ph.D. is more demanding. Master's students who are planning to pursue a Ph.D. degree should satisfy the Ph.D. version of the breadth requirements.

The department will accept at most 9 credit hours of transfer credit from other graduate programs. If appropriate, this transferred credit may be used to satisfy Breadth Requirement bins. These credits must not have been used to satisfy the requirements of another academic degree earned by the candidate. With rare exceptions, these credits are limited to courses taken before matriculation at WPI.

A student may count a total of at most two courses towards their M.S. degree from the following categories: preparatory CS courses and courses from other departments. For example: 2 preparatory courses; or 2 courses from another department; or 1 preparatory course plus 1 course from another department.

#### Thesis Option

At least 33 credit hours, including the thesis, must be satisfactorily completed. 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 must take four courses satisfying the Breadth Requirement; these courses should be taken as early as possible in the student's program. The remaining courses may, with prior approval of the student's advisor, consist of computer science courses, independent study, or courses elected from other disciplines. At most, two courses in other disciplines will be accepted. *Courses*

*in college teaching may not be counted towards the 33 credits required for a CS Master's degree.*

Students funded by a teaching assistantship, research assistantship or fellowship must complete the thesis option.

### **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. The remaining seven courses may, with prior approval of the student's advisor, consist of computer science courses, independent study, or courses elected from other disciplines. *Courses in college teaching may not be counted towards the 33 credits required for a CS Master's degree.*

Students funded by a teaching assistantship, research assistantship or fellowship must complete the thesis option.

### **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 Directed Research Requirement. These requirements are described in the Graduate Regulations on the CS department web site <http://www.cs.wpi.edu/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.

### **Research Interests**

The current departmental activities include, among other areas, analysis of algorithms, applied logic, artificial intelligence, computer vision, computer graphics, database and information systems, data mining, distributed systems, graph theory and computational complexity, intelligent tutoring systems, 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.

### **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'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.

### **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.

### **Faculty**

**M. A. Gennert**, Associate Professor and Department Head; Sc.D., Massachusetts Institute of Technology, 1987. Image processing; image understanding; artificial intelligence; scientific databases; theoretical computer science.

**Emmanuel O. Agu**, Associate Professor; Ph.D., Massachusetts, 2001. Computer graphics, wireless networking, and mobile computing.

**Joseph E. Beck**, Assistant Professor; Ph.D., Massachusetts, 2001. Machine learning, educational data mining, intelligent tutoring systems, human learning and problem solving.

**David C. Brown**, Professor; Ph.D., Ohio State, 1984. Knowledge-based design systems, artificial intelligence.

**Sonia Chernova**, Assistant Professor; Ph.D., Carnegie Mellon University, 2009. Artificial intelligence, autonomous systems, robot learning, human-robot interaction, adjustable autonomy, multi-robot systems.

**Mark L. Claypool**, Professor; Ph.D., Minnesota, 1997. Distributed systems, networking, multimedia and online games.

**Daniel J. Dougherty**, Professor; Ph.D., Maryland, 1982. Logic in computer science.

**David Finkel**, Professor; Ph.D., Chicago, 1971. Computer system performance evaluation, distributed computing systems, focusing on the performance of computer networks and distributed systems.

**Kathi Fisler**, Associate Professor; Ph.D., Indiana, 1996. Interplay of human reasoning and formal logic in the context of hardware and software systems; current projects explore access-control policies and diagrams.

**Joshua D. Guttman**, Professor; Ph.D., Chicago, 1984. Information security, logic and formal methods, mechanized reasoning, programming languages.

**Neil T. Heffernan**, Associate Professor; Ph.D., Carnegie Mellon, 2001. Intelligent tutoring agents, artificial intelligence, cognitive modeling, machine learning.

**George T. Heineman**, Associate Professor; Ph.D., Columbia, 1996. Component-based software engineering, formal approaches to compositional design.

**Micha Hofri**, Professor; Ph.D., Technion (Israel), 1972. Analysis of algorithms, performance evaluation, applied probability, the use of statistics in algorithms, asymptotics.

**Robert E. Kinicki**, Professor; Ph.D., Duke, 1978. Computer network performance, wireless networks, multimedia streaming.

**Karen A. Lemone**, Professor Emeritus; Ph.D., Northeastern, 1979. Electronic documents, language translation.

**Robert W. Lindeman**, Associate Professor; Ph.D., George Washington, 1999. Human-computer interaction, haptics, virtual environments.

**Charles Rich**, Professor; Ph.D., Massachusetts Institute of Technology, 1980. Artificial intelligence and its intersections with human-computer interaction, interactive media and game development, robotics, intelligent tutoring systems, knowledge-based software tools.

**Carolina Ruiz**, Associate Professor; Ph.D., Maryland, 1996. Data mining, knowledge discovery in databases, machine learning.

**Elke A. Rundensteiner**, Professor; Ph.D., California, Irvine, 1992. Database and information systems, stream and sensor query processing, and information integration.

**Gabor N. Sarkozy**, Affiliate Associate Professor; Ph.D., Rutgers, 1994. Graph theory, combinatorics, algorithms.

**Stanley Selkow**, Professor; Ph.D., Pennsylvania, 1970. Combinatorial algorithms, graph theory, analysis of algorithms.

**Matthew O. Ward**, Professor; Ph.D., Connecticut, 1981. Data and information visualization, spatial data analysis and management.

**Craig E. Wills**, Professor; Ph.D., Purdue, 1988. Distributed systems, networking, user interfaces.

## Course Descriptions

All courses are 3 credits unless otherwise noted.

### 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 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 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 BS 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/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 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 ECE 502 or equivalent background in CS 5084 or CS 584.)

### **CS 514/ECE 572. Advanced Systems Architecture**

See ECE 572 course description on page 73.

### **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 useful 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.) See the **SUPPLEMENT** section of the on-line catalog at [www.wpi.edu/+gradcat](http://www.wpi.edu/+gradcat) for descriptions of courses to be offered in this academic year.

### **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 530/ECE 530. High-Performance Networks**

This course is an in-depth study of the theory, design and performance of high-speed networks. Topics include specific high-performance network implementations 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: CS 513/ECE 506.)

### **CS 531. System Simulation**

The theory and design of discrete simulations are discussed. Other topics are random number generations, analysis of output and optimization. (Prerequisites: CS 504 or equivalent background in probability and some background in statistics.)

### **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. Several basic techniques such as search methods, formal proofs and knowledge representation are covered. Selected topics involving the applications of these tools are investigated. Such topics might include natural language understanding, scene understanding, game playing, learning and planning. (Prerequisites: familiarity with data structures and a recursive high-level language. Knowledge of LISP is an advantage.)

### **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.) See the **SUPPLEMENT** section of the on-line catalog at [www.wpi.edu/+gradcat](http://www.wpi.edu/+gradcat) for descriptions of courses to be offered in this academic year.

### **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 database 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, CS 504, or CS 584.)

### **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 mined 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 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 representa-

tions for visual information, including sketches and intrinsic images. (Prerequisites: CS 534, CS 543, CS 545, or the equivalent of one of these courses.)

#### **CS 556. Foundational Aspects of Database Systems**

This course will cover the logic-based foundations of database systems. The theory and implementation of advanced query languages such as datalog will be a central focus: typical topics include fixed-point semantics of recursive queries, checking safety of queries, implementation techniques such as fix-point and magic sets, and advanced optimization techniques such as join-minimization and decorrelation. Other topics covered will include theoretical foundations of data integration, as well as algorithms and techniques for data warehousing and view maintenance. (Prerequisites: CS 542 or equivalent.)

#### **CS 559. Advanced Topics in Theoretical Computer Science**

This course has an instructor-dependent syllabus. See the **SUPPLEMENT** section of the on-line catalog at [www.wpi.edu/+gradcat](http://www.wpi.edu/+gradcat) for descriptions of courses to be offered in this academic year.

#### **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.) See the **SUPPLEMENT** section of the on-line catalog at [www.wpi.edu/+gradcat](http://www.wpi.edu/+gradcat) for descriptions of courses to be offered in this academic year.

#### **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.) See the **SUPPLEMENT** section of the on-line catalog at [www.wpi.edu/+gradcat](http://www.wpi.edu/+gradcat) for descriptions of courses to be offered in this academic year.

#### **CS 563. Advanced Topics in Computer Graphics**

This course examines one or more selected current issues in the area of image synthesis. Specific topics covered are dependent on the instructor. Potential topics include: scientific visualization, computational geometry, photo-realistic image

rendering and computer animation. (Prerequisite: CS 543 or equivalent.) See the **SUPPLEMENT** section of the on-line catalog at [www.wpi.edu/+gradcat](http://www.wpi.edu/+gradcat) for descriptions of courses to be offered in this academic year.

#### **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 513/ ECE 506 and CS 533/ECE 581.)

#### **CS 578/ECE 578. Cryptography and Data Security**

See ECE 578 course description.

#### **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 BS in Computer Science.

#### **CS 595/ECE 595. Computer and Communications Networks Internship** 6 credits

This project will provide an opportunity to put into practice the principles which have been studied in previous courses. It will generally be conducted off campus and will involve a real-world networking situation. Overall conduct of the internship will be supervised by a WPI faculty member and an on-site liaison will direct day-to-day activity. The project must include substantial analysis and/or design related to computer or communications networking 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. Successful completion of the internship will be verified by this committee. For a student from industry, an internship may be sponsored by his or her employer. (Prerequisite: completion of 12 credits of the CCN program; CS 598 Directed Research, CS 599 Master's Thesis, or CS 699 Ph.D. Dissertation.)

#### **CS 598 Directed Research**

#### **CS 599 Master's Thesis**

#### **CS 699 Ph.D. Dissertation**

## Programs of Study

The Electrical and Computer Engineering (ECE) Department offers programs leading to the M.Eng., M.S. and Ph.D. degrees in electrical and computer engineering, as well as graduate and advanced certificates. The following general areas of specialization are available to help students structure their graduate courses: bio-medical signal processing/instrumentation, communications and signal processing, computer engineering, electromagnetics and ultrasonics engineering, electronics and solid state, power engineering, and systems and controls.

The M.S. 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 senior-level undergraduate and graduate courses from computer science, mathematics, physics and other engineering disciplines.

The M.Eng. degree is 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. 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 two degree options in the Master's program in electrical and computer engineering: the Master of Science (M.S.) and the Master of Engineering (M.Eng.) 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 electrical and computer engineering. 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 of science 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 an 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.

## Degree Requirements

### For the Master's Degree Program

There are two degree options in the Master's program in electrical and computer engineering; The Master of Engineering (M.Eng.) and the Master of Science (M.S.).

Students pursuing the M.S. 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 level or above) in the field of electrical and computer engineering (course prefix ECE) offered by WPI. The remaining courses may be either at the 4000 (maximum of two) or the 500 level in computer science (CS), physics (PH), engineering (BME, CHE, CE, FP, MFE, MTE, ME, and RBE) and/or mathematics (MA). The complete program must be approved by the student's advisor and the Graduate Program Committee.

Students pursuing the M.Eng. degree require 30 graduate credits in course work, independent study, or directed research. There is no thesis option for the M.Eng. degree program. At least 21 of the 30 credits must be graduate level activity (designated 500 level or above) in the field of electrical and computer engineering (course prefix ECE) offered by WPI. The remaining courses may be either at the 4000 level (maximum of two) or at the graduate level in computer science (CS), physics (PH), engineering (BME, CHE, CE, FP, MFE, MTE, ME, and RBE), mathematics (MA), and/or management (ACC, ETR, FIN, MIS, MKT, OBC, and OIE). The complete program must be approved by the student's advisor and the Graduate Program Committee.

### 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 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. 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. 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. students not financially supported by the department, and there is no thesis option available for M.Eng. 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. degree or non-thesis M.S. 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 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 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 PhD 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 PhD 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 certifies 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. degree via this particular program. At least 6 credit hours must be 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.

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.”

## Electrical and Computer Engineering Research Laboratories/Centers

### Analog Microelectronics Laboratory

*Prof. McNeill*

The Analog Microelectronics Laboratory was opened in 1998, funded by NSF grants for the purchase of test and measurement equipment, which is dedicated to support work in the areas of high-speed data communication, high-speed imaging, and mixed signal circuit design. In addition to the direct impact on research, this equipment has also enabled the Analog Microelectronics Laboratory to become a valuable resource for educating both undergraduates and graduate students in the complete integrated circuit (IC) design process.

Current research in the lab is focused on self-calibrating analog-to-digital converters (ADCs) and mixed-signal IC design for biomedical applications.

### Antenna Laboratory

*Prof. Makarov*

This laboratory contains facilities for the simulation and development of basic communication antennas. The laboratory is equipped with high-frequency network analyzers, spectrum analyzers, broadband RF amplifiers, and signal generators. Supported software systems include Ansoft HFSS/Maxwell3D simulators (multiple server licenses), and custom MoM codes. The laboratory has been particularly active in the area of antenna array design.

### Center for Wireless Information Networking Studies (CWINS)

*Prof. Pablavan*

Started in 1985, this center is recognized as a worldwide pioneering facility in wireless access and localization technique in indoor areas. Research at the CWINS is supported by a broad range of wireless networking corporations and government agencies and it is quite multi-disciplinary

and focused on systems engineering. The core competence of the laboratory resides on understanding of radio propagation for different applications. The laboratory is known for its seminal research in Wireless LAN application and pioneering research in indoor geolocation. Currently, CWINS is involved in RF propagation studies for wireless access and localization in Body Area Networks and cooperative localization for Robotics applications.

### Computational Fields Laboratory

*Prof. Ludwig*

The purpose of this laboratory is to serve as a computational resource to undergraduate and graduate students interested in numerical analysis as applied to problems in computational electrodynamics and acoustics. The lab contains a wide variety of platforms, including Pentium-class PCs and several workstations for X-window applications. Software utilities supporting numerical analysis (mesh-making algorithms, matrix solvers, graphics interface drivers) are of particular interest to the lab community, as is the development of integrated packages targeted for research or educational purposes.

### Embedded Computer Systems Laboratory

*Prof. Duckworth*

This laboratory contains facilities for the research and development of embedded computer systems. The laboratory is also equipped with logic analyzers, in-circuit emulators and other equipment to support computer system projects. Software systems supported by this laboratory include several VHDL/FPGA development systems, as well as a variety of software development tools (C, CTT, ASW, PIC developments, and so forth).

The laboratory is also equipped with logic analyzers, in-circuit emulators and other equipment to support computer system projects. Software systems supported by this laboratory include various VLSI design and verification packages, several VHDL/FPGA development systems, and a variety of software development tools (C, CTT, ASW, PIC developments, and so forth).

## Convergent Technologies Center (CTC)

*Prof. Cyganski*

The laboratories in this center combine diverse expertise for the exploration of the emerging and converging technologies of computing, communications and cognition. The Polaroid Machine Vision Laboratory (PMVL), and Network Computing Applications and Multimedia (NETCAM) laboratory focus on the development of new algorithms and on moving emergent technologies into commercial, medical and defense-related applications for its sponsors.

Research in the CTC's NETCAM lab derives from the technologies generated by the success of the Internet, digital multimedia, and distributed objects and middleware. Current projects explore the optimization of network protocols for multimedia, distributed-object services (CORBA) and virtual-reality-based user interfaces.

Research in the CTC's PMVL has resulted in the development of highly efficient algorithms and new theoretical performance bounds for machine vision, automatic target recognition, and image fusion for optical, IR SAR and SONAR data.

### Laboratory for Sensory and Physiologic Signal Processing – L(SP)<sup>2</sup>

*Prof. Clancy*

Researchers within the C(SP)<sup>2</sup> apply signal processing, mathematical modeling, and other electrical and computer engineering skills to study applications involving electromyography (EMG — the electrical activity of skeletal muscle). We 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.

### Power Electronics and Power Systems Laboratory

*Prof. Clements, Emanuel*

This laboratory has been established for simulation of a large variety of linear, non-linear and time-varying loads, including transistor- and thyristor-controlled loads. It contains transducers and instrumentation for a wide range of voltages, currents

and frequencies. Compatible computer equipment and A/D interfaces are available for real-time data acquisition and processing. The Power Systems Laboratory has the basic facilities for electromechanical energy conversion study, including sets of induction/ synchronous/DC machines coupled together.

### **Center for Advanced Integrated Radio Navigation (CAIRN)**

*Prof. Michalson*

This laboratory provides facilities for work on civilian uses of satellite systems, especially the Global Positioning System (GPS). Receivers, signal processors and computers are provided for work on utilization of the DOD GPS system for civilian purposes, especially aircraft navigation and landing.

### **Ultrasound Research Laboratory**

*Prof. Pedersen*

The mission of the Ultrasound Research Lab is to enable a wider use of medical ultrasound so that it can be used by medical personnel with modest training. To that end, we are implementing a mobile, rugged ultrasound imaging system, augmented with an exam camera and physiological sensors, and with the ability to wirelessly stream ultrasound and visual images as well as voice.

The Ultrasound Research Lab is developing a low-cost tool for training clinicians in medical ultrasound imaging. To make the ultrasound image easier to interpret, we are developing image analysis algorithms, to aid the interpretation of the image for trauma situations. Separately, we have ongoing research in elastography and in atherosclerotic plaque classification.

### **Cryptography and Information Security (CRIS) Laboratory**

*Prof. Sunar*

The CRIS Laboratory conducts research and development in cryptography and its applications. One research focus is efficient implementations of the next generation of private and public-key algorithms in emerging infrastructures such as wireless sensor and RFID enabled networks.

Furthermore, we develop state-of-the-art techniques for cryptographic error detection and tamper-resilience. We also develop fast software algorithms and ef-

ficient hardware architectures. The lab is equipped with industry-standard development tools for ASIC and FPGA target hardware.

The CRIS lab is actively involved in a number of joint projects with industry. The lab has also strong ties to research groups in the United States and Europe, with frequent exchange of graduate students. Together with strong graduate course offerings in cryptography, WPI's research lab provides excellent opportunities for cutting-edge research and graduate education.

### **Signal Processing and Information Networking Laboratory (SPINLab)**

*Prof. Brown*

SPINLab was established in 2002 with the primary mission of analyzing and developing new linear and nonlinear signal processing techniques to improve the performance of high-speed information networks. Currently, our major focus areas include channel identification and equalization, synchronization, interference cancellation, and multiuser detection for copper, optical and wireless channels. We have also recently begun to study software radio techniques for efficient implementation of digital communication systems and signal processing algorithms. SPINLab has established relationships with several telecommunications corporations and offers research opportunities at both the graduate and undergraduate levels. For more details, please see the SPINLab Web page at <http://spinlab.wpi.edu>.

### **Wireless Innovation Laboratory (WILab)**

*Prof. Wyglinski*

The Wireless Innovation Laboratory (WILab) was established in 2007 in order to advance our understanding of technologies and algorithms that can help improve society's usage of radio frequency spectrum for a wide range of wireless applications. Several research activities currently underway at WILab include the following: (1) Development and realization of high-speed spectrally agile waveforms for opportunistic spectrum access networks. (2) Implementation of practical wireless device optimization techniques for rapidly selecting near-optimal operating param-

eters to enhance overall system performance. (3) Prototyping of innovative and novel wireless networking system designs using software-defined radio development platforms. (4) Creation of novel distributed network architectures exploiting the agility of cognitive radios and the dynamic spectrum access paradigm. (5) Introduction of "learning" into cognitive radio platforms for complete automation of the operating parameter selection process. Research infrastructure for WILab consists of several high-performance computer workstations, four software-defined radio development platforms, an Agilent CSA N1996A spectrum analyzer, an array of discone and horn antennas, and several simulation software packages. For more details, please see the WILab website at <http://www.Wireless.WPI.edu>.

### **Wireless Networking and Security Laboratory (WiNetS)**

*Prof. Lou*

The mission of WiNetS is to explore the novel concepts and ideas related to the protocols and systems of wireless and mobile networking, and to design scalable architecture and efficient and secure protocols for the next generation wireless networks. Our current research interests include security in wireless networks and information systems, capacity analysis and routing/ MAC protocol design in multi-hop wireless networks, and cyber-physical systems.

### **Wireless Communications and Adaptive Signal Processing (WASP) Laboratory**

*Prof. Klein*

Mission: Studying a range of problems relating to both the basic theory as well as practical design strategies for next-generation wireless communication networks. The research employs tools from a variety of areas, including communication and information theories, statistical signal processing, and adaptive parameter estimation.

Representative research:

- Exploiting frequency selectivity in cooperative communication links
- Practical transceiver design for cooperative and relay communication systems
- Adaptive digital compensation of RF front-end non-idealities

## Faculty

**Fred J. Looft**, Professor and Department Head; Ph.D., Michigan. Digital and analog systems, microprocessor and embedded systems, space-flight systems, robots and robotic systems, robot sensors, alternative energy systems.

**Donald R. Brown**, Associate Professor; Ph.D., Cornell University. Network protocols cooperate communication in networks, interference mitigation for multiuser communication systems, adaptive channel equalization, signal processing applications.

**Edward (Ted) A. Clancy**, Associate Professor; Ph.D., MIT. Biomedical signal processing and modeling, biomedical instrumentation.

**Kevin A. Clements**, Professor Emeritus; Ph.D., Polytechnic Institute of Brooklyn. Electric power systems, controls, signal processing.

**David Cyganski**, Professor; Ph.D., Worcester Polytechnic Institute. Optimization and security of Internet communications, distributed and fault tolerant computing, CORBA, and problems related to machine vision and automatic target recognition.

**James S. Demetry**, Professor Emeritus; Ph.D., Naval Postgraduate School. Control systems design and analysis, computer-assisted instruction.

**R. James 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.

**Wilhelm H. Eggimann**, Professor Emeritus; Ph.D., Case Western Reserve. Computer engineering, VLSI, electromagnetic fields.

**Alexander E. Emanuel**, Professor; D.Sc., Israel Institute of Technology. Power quality, power electronics, electromagnetic design, high-voltage technology.

**Ximing Huang**, Assistant Professor; Ph.D., Virginia Tech. Reconfigurable computing, VLSI integrated circuits, networked embedded systems.

**Hossein Hakim**, Associate Professor and Associate Department Head; Ph.D., Purdue University. Digital signal processing, system engineering.

**Andrew Klein**, Assistant Professor; Ph.D., Cornell University. Signal processing for communication systems, cooperative networks, adaptive parameter estimation, and equalization.

**Wenjing Lou**, Associate Professor; Ph.D., University of Florida. Wireless networks, ad-hoc networks, computer networks, with an emphasis on routing and network security.

**Reinhold Ludwig**, Professor; Ph.D., Colorado State University. Electromagnetic and acoustic nondestructive evaluation (NDE), electromagnetic/acoustic sensors, electromechanical device modeling, piezoelectric array transducers, numerical simulation, inverse and optimization methods for magnetic resonance imaging (MRI).

**Sergey N. Makarov**, Professor; Ph.D., St. Petersburg State University (Russia). Antennas: numerical simulation, broadband and ultrawideband antennas, frequency selective surfaces, metal photonic elements, metal lenses.

**John A. McNeill**, Associate Professor and Co-Director of the Limerick, Ireland, Project Center; Ph.D., Boston University. Mixed signal integrated circuit design.

**William 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.

**John A. Orr**, Professor; Ph.D. University of Illinois at Urbana-Champaign. Digital signal processing, image analysis/pattern recognition, power quality, communications.

**Kaveh Pahlavan**, Professor; Ph.D., Worcester Polytechnic Institute. Sensor and ad hoc wireless networks, indoor geolocation, data communication, information networks.

**Peder C. Pedersen**, Professor 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.

**Robert A. Peura**, Professor Emeritus; Ph.D., Iowa State University. Biomedical instrumentation and biosensors; non-invasive measurement of blood glucose and urea; impedance imaging and spectroscopy.

**Berk Sunar**, Associate Professor; Ph.D., Oregon State University. Cryptography and network security, high-performance computing and error control codes.

**Richard 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.

**Alexander M. Wyglinski**, Assistant Professor and Director of the Limerick, Ireland, Project Center; Ph.D., McGill University. Wireless communications, cognitive radio, software-defined radio, transceiver optimization, dynamic spectrum access networks, signal processing for digital communications, wireless networks.

## 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, multiprogramming, 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/CS513. 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 queuing 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 receive credit for ECE 573 may not receive credit for ECE 506.)

### **ECE 512. Acoustic and Ultrasound Engineering**

Fundamentals of vibration. The acoustic wave equation, transmission phenomena, absorption and attenuation. Radiation from acoustic sources, dipole and line source radiation, planar piston source, radiation patterns, beam width, directivity, fields from pulsed transducers, Green's function, diffraction, reciprocity. Techniques for ultrasound modeling. Acoustic waveguides. Ultrasound transducer types and transducer modeling. Transducer characterization and calibration. Acoustic measurement techniques. (Prerequisites: ECE 502 and ECE 504 or equivalent, undergraduate course in modern signal theory, undergraduate course in E/M field theory, or permission of the instructor.)

### **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 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. See the SUPPLEMENT section of the on-line catalog at [www.wpi.edu/+gradcat](http://www.wpi.edu/+gradcat) for descriptions of courses to be offered in this academic year.

### **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 specific 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 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 535. Telecommunications Transmission Technologies**

This course introduces the principle technologies used to implement the physical networking layer. These include high-speed electronic pulse shapers and receivers, optical sources, detectors, fiber media, active optical elements, RF devices and systems, and the related protocols and modulation schemes for reliable and multi-user communications (time, frequency, space and code-division multiplexing, error correction coding, spectral reuse, and so on). The course includes laboratory experiments. (Prerequisites: ECE 502 or CS 504; undergraduate-level understanding of signal and circuit theory.)

### **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 multi-amplitude 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 HIPER-LAN. (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 Communication Theory and Signal Processing. See the **SUPPLEMENT** section of the on-line catalog at [www.wpi.edu/+gradcat](http://www.wpi.edu/+gradcat) for descriptions of courses to be offered in this academic year.

### **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. See the **SUPPLEMENT** section of the on-line catalog at [www.wpi.edu/+gradcat](http://www.wpi.edu/+gradcat) for descriptions of courses to be offered in this academic year.

### **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. See the **SUPPLEMENT** section of the on-line catalog at [www.wpi.edu/+gradcat](http://www.wpi.edu/+gradcat) for descriptions of courses to be offered in this academic year.

### **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. See the **SUPPLEMENT** section of the on-line catalog at [www.wpi.edu/+gradcat](http://www.wpi.edu/+gradcat) for descriptions of courses to be offered in this academic year.

### **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 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 synthesis 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.)

### **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. See the **SUPPLEMENT** section of the on-line catalog at [www.wpi.edu/+gradcat](http://www.wpi.edu/+gradcat) for descriptions of courses to be offered in this academic year.

### **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 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.)

### **ECE599. 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 data 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 cryptosystems, 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 cryptanalysis (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**

## Programs of Study

Fire protection engineers specialize in applying modern technology to the solution of firesafety problems. The successful fire protection engineer must know something about building construction and industrial processes; must interact with and be somewhat competent in other design professions including architecture and electrical, mechanical, civil and chemical engineering. In addition, the firesafety aspects of human behavior, business, management and public administration are important aspects of practice.

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 or power), 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 Advanced Distance Learning Network (see page 11) 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.

## 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.

## 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 Ph.D. applicants, and strongly recommended for all others.

## 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.

## 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. 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 by alternating work with on-campus classroom and laboratory activities. With departmental permission, students may take courses during the full-time work cycle. For more information, contact the Department of Fire Protection Engineering.

## Research Interests

Faculty research interests cover 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.

Specific capabilities and interests include computer modeling, fire performance of structural systems, fire detection and suppression, fire and smoke dynamics, firesafety design methods for buildings and marine applications, explosion phenomena, failure analysis, risk assessment, material composites and regulatory reform.

## Research Laboratories

### Fire Science Laboratory

This laboratory facility supports 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.

The wet lab area supports water-based fire suppression and demonstration projects.

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 Combustion 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.

## Faculty

### Core FPE Program Faculty

**K. A. Notarianni**, Associate Professor and Department Head; Ph.D., Carnegie Mellon University; Fire detection and suppression; high-bay fire protection; fire policy and risk; uncertainty; performance-based design; engineering tools.

**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

**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**, Assistant 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**, Assistant 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

**J. Averill**, Adjunct Assistant Professor; performance-based codes and economics, human behavior in fires, egress and emergency communications, applications of computer fire models to fire safety engineering problems, fire safety of passenger trains, smoke alarm operability in residential fires and hazard analysis

**D.T. Sheppard**, Adjunct Assistant Professor; Fire incident investigation; failure analysis; computer modeling; large-scale and small-scale experimental test programs; fire dynamics; fire origin and cause; courtroom testimony as expert witness

**J. Tubbs**, Adjunct Assistant Professor; Consulting, large unique building design, smoke control systems, detection and alarm, egress from fire

**C. Wood**, Adjunct Assistant 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

## Course Descriptions

All courses are 3 credits unless otherwise noted.

### FPE 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: FPE 521 or permission of the instructor.)

### FPE 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.)

### FPE 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.)

### FPE 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: FPE 553 or special permission of instructor.)

### FPE 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: FPE 553 and FPE 521, which can be taken concurrently.)

### FPE 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.

### FPE 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: FPE 553, FPE 521 and FPE 570, or special permission of the instructor.)

### FPE 572. Failure Analysis

Development of fire investigation and reconstruction as a basis for evaluating and improving firesafety 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: FPE 521, FPE 553, FPE 570 or special permission of the instructor.)

### FPE 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: FPE 553, FPE 521 or special permission of the instructor.)

### FPE 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.

### FPE 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. See the SUPPLEMENT section of the on-line catalog at [www.wpi.edu/+gradcat](http://www.wpi.edu/+gradcat) for descriptions of courses to be offered in this academic year.

- Business Practice
- Combustion
- People in Fires
- Fire Risk and Regulatory Policy

### FPE 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 velocity, gas species and heat fluxes, infrared thermometry, laser doppler velocimetry (LDV) and laser-induced fluorescence (LIF) will be reviewed. (Prerequisite: FPE 521.)

### FPE 590. Thesis

Research study at the M.S. level.

### FPE 690. Ph.D. Dissertation

# 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 80), Systems Modeling (see page 121), and Social Science (see page 122).

Students may also design their own interdisciplinary Ph.D. program in consultation with faculty members relevant to the proposed project.

## 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 (see page 122), Construction Project Management (see page 52), Impact Engineering, Manufacturing Engineering Management, Power Systems Management, Systems Engineering, and Materials Systems Engineering.

## 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 at 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 (IDG501, 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 (in 2009-2010, \$290/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 web site at [www.cowc.org/CCT.htm](http://www.cowc.org/CCT.htm) under "Procedures for Students."

## Questions

Contact Chrysanthe Demetry, Ph.D.  
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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.

## Program of Study

The Learning Sciences and Technologies (LS&T) program offers graduate studies toward the MS and PhD 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 PhD 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 or Dr. Janice Gobert.

## Degree Requirements

### M.S. Requirements

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 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.

### MS 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 MS graduate credits cannot be from independent study/research courses except by approval of the LS&T Program Director.

### MS 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 BS/M.S. Degree

The LS&T program does not offer a combined B.S./M.S. degree.

## Ph.D. Requirements

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 appropri-

ate 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 MS 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

## Faculty

### Learning Sciences & Technologies

#### Core Faculty

**Neil T. Heffernan**, Associate Professor and Executive Director; Ph.D., Carnegie Mellon University; Intelligent tutoring agents, artificial intelligence, cognitive modeling, machine learning

**Janice Gobert**, Associate Professor and Director; Ph.D., University of Toronto; learning with visualizations and simulations in science; learning and assessment with technology; learner characteristics and their relationship to content learning

**Ryan S.J.d. Baker**, Assistant Professor; Ph.D., Carnegie Mellon University; educational data mining, learner-computer interaction, gaming the system, student modeling, intelligent tutoring systems, educational games

**Joseph E. Beck**, Assistant Professor; Ph.D., University of Massachusetts, Amherst; educational data mining, student modeling, Bayesian Networks, student individual differences

### Learning Sciences & Technologies Associated Faculty

**David C. Brown**, Professor; Ph.D., Ohio State University; Knowledge-based design systems, artificial intelligence

**James K. Doyle**, Associate Professor; Ph.D., University of Colorado/Boulder; judgement and decision making, mental models of dynamic systems, evaluation of interventions

**Kathi 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.

**George T. Heineman**, Associate Professor; Ph.D., Columbia University; Component-based software engineering, formal approaches to compositional design

**Arthur C. Heinricher**, Professor; Ph.D., Carnegie Mellon University; applied probability, stochastic processes and optimal control theory

**Robert W. Lindeman**, Associate Professor; Ph.D., George Washington University; Human-computer interaction, haptics, virtual environments

**Charles Rich**, Professor; Ph.D., Massachusetts Institute of Technology; Artificial intelligence and its intersections with human-computer interaction, interactive media and game development, robotics, intelligent tutoring systems, knowledge-based software tools

**Carolina Ruiz**, Associate Professor; Ph.D., University of Maryland; Data mining, knowledge discovery in databases, machine learning

**Jeanine L. Skorinko**, Assistant Professor; Ph.D., University of Virginia; social environmental cues, stigmas and stereotyping, perceptions of others

## Course Descriptions

All courses are 3 credits unless otherwise noted.

### 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.)

### 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.)

### 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 and 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 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.)

### **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)

### **PSY 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 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 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.)

## 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. Some 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 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 530 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 574 Enterprise Systems

### 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 540 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 574 Enterprise Systems 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 which is based on the material in four of the eight core areas required for the M.S. degree in MFE. 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 and, generally, externally sponsored 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.

## 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.

## Research Facilities and Laboratories

The program has access to extensive research facilities through the Computer Aided Manufacturing (CAM) Lab, the HAAS Technical Center, the Production and Machine Dynamics Lab, the Robotics Lab and the Surface Metrology Lab.

## 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 creates 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 and the dissemination of new knowledge. More than 120 private manufacturers participate in the Institute, and their support helps fund fundamental and applied research that addresses technological barriers facing the industry. The MPI researchers also develop and demonstrate best practices and state-of-the-art processing techniques.

## Center for eHealth Innovation and Process Transformation (CeHIPT)

The Center for eHealth Innovation and Process Transformation is an interdisciplinary center involving faculty from the Management and Mechanical Engineering Departments. The goal of the center is to use and expand engineering and management information systems knowledge to improve health care delivery using lean manufacturing, quality improvement, and systems design approaches. The center team studies health care delivery innovations and the dynamics of change as related to the implementation and use of electronic medical records, telemedicine, lean processes, and personal health records.

**The CAM Lab** includes several UNIX and PC-based engineering graphics workstations used for CAD, solid modeling, kinematic analysis, FEA, CIM and expert system development, and a number of computers set up for data acquisition and real-time control. The lab has been developing techniques and systems for process (machining and heat treatment) modeling and simulation, production planning, tolerance analysis, and fixture design.

**The HAAS Technical Center** at WPI, supported in partnership with HAAS Automation (Oxnard, California), includes eleven CNC machine tools and four simulators, linked to the Web, and eight workstations in the manufacturing design studio. The center supports teaching and research on computer-controlled machining, as well as the fabrication of equipment for projects and research. The machines are selected to accommodate a wide variety of applications and include two vertical machining centers and a lathe with live tooling, as well as smaller lathes and mills.

## The Production and Machine

**Dynamics Lab** uses a variety of techniques, including innovative computerized modeling and computer-controlled data acquisition, to understand the vibrations that occur during machining, which limit productivity and part quality.

**The Robotics Lab** equipment includes a number of industrial robots set up for deburring, welding, assembly and metrology; a Coordinate Measurement Machine (CMM) with data acquisition and GD&T software; a machining area with CNC machine tools; and a range of specialized automation equipment interfaced to PLCs.

**The Surface Metrology Lab** has two scanning laser microscopes as well as conventional profilers. The lab has developed new texture measurement techniques and analysis methods and has pioneered the development of application of scale-sensitive fractal analysis, to study how surface texture, or roughness, influences behavior and how surface texture is influenced by manufacturing processes, wear, fracture, disease, growth and corrosion. The Surface Metrology Lab collaborates with labs in the United States, Canada, Europe and Chile on projects including food science, skin, pavement friction, hard drive stiction, abrasive finishing, adhesion, and more.

## 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.

**Y. K. Rong**, John Woodman Higgins Professor; Associate Director, Manufacturing and Materials Engineering; Ph.D., University of Kentucky. CAD/CAM, manufacturing process and systems.

**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 life prediction, and electronic packaging.

**C. A. Brown**, Professor; Director, Surface Metrology Lab; Director, Haas Technical Center; Ph.D., P.E., University of Vermont. Surface metrology, machining, fractal analysis, sports engineering, tribology, axiomatic design and abrasive processes.

**Mustapha S. Fofana**, Associate Professor; Ph.D., University of Waterloo, Canada, 1993; Nonlinear chatter dynamics, delay systems, CAD/CAM, CIM/Networked manufacturing systems.

**S. A. Johnson**, Associate Professor and Director of Industrial Engineering; Ph.D., Cornell University

**M. M. Makhlof**, Professor; Director, Aluminum Casting Research Laboratory; Ph.D., WPI. 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.

**J. M. Sullivan Jr.**, Professor of Mechanical Engineering; D.E., Dartmouth College

**B. Tulu**, Assistant Professor of Management, Ph.D. Claremont Graduate University, medical informatics, information security, telemedicine, personal health records, systems analysis and design

**A. Zeng**, Associate Professor of Industrial Engineering; Ph.D., Pennsylvania State University

## 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/ME 542. Control and Monitoring of Manufacturing Processes**

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**

(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/MTE520/ME 543. Design and Analysis of Manufacturing Processes**

The first half of the course covers the axiomatic design method, applied to simultaneous product and process design for concurrent engineering, with the emphasis on process and manufacturing tool design. Basic design principles as well as qualitative and quantitative methods of analysis of designs are developed. The second half of the course addresses methods of engineering analysis of manufacturing processes, to support machine tool and process design. Basic types of engineering analysis are applied to manufacturing situations, including elasticity, plasticity, heat transfer, mechanics and cost analysis. Special attention will be given to the mechanics of machining (traditional, nontraditional and grinding) and the production of surfaces. Students, work in groups on a series of projects.

### **MFE 530/ME 544. Computer-Integrated Manufacturing**

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, feature-based computer-aided design, setup planning and production line analysis, tooling and fixture design, and manufacturing information systems. This course includes a group term project. (Prerequisites: Background on manufacturing and CAD/CAM, e.g., ME 1800, ES 1310, ME 3820.)

### **MFE 540. Design for Manufacturability**

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.

### **MFE 594. Special Topics**

Theoretical and experimental studies in subjects of interest to graduate students in manufacturing engineering. (Prerequisite: Consent of instructor.) See the SUPPLEMENT section of the on-line catalog at [www.wpi.edu/+gradcat](http://www.wpi.edu/+gradcat) for descriptions of courses to be offered in this academic year.

### **MFE 598. Directed Research**

3 to 6 credits

### **MFE 599. Thesis Research**

Maximum 3 credits

### **MFE/MTE 5822. Solidification Processes**

processes based on liquid-solid transformations. Fundamentals are developed and applied to commercial processes. The topics covered include qualitative treatment of casting processes, sand casting, die casting, investment casting, semisolid forming, various welding processes, laser welding, rapid solidification, spray forming, compocasting and other emerging technologies which utilize liquid-solid transformations. Library and laboratory work will be included. (Suggested preparation: an understanding of heat transfer, fluid flow, solid state diffusion and microscopy [ES 2001, ES 3003, ES 3004, ME 3811, ME 4840] or equivalent.)

### **MFE/MTE/ME 5841. Surface Metrology**

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.

## 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 new 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 & Engineering

### Management/Industrial Engineering

## Admission Requirements

Admission requirements include a B.S. in engineering or science and at least three years of industrial experience. 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 in management are available through WPI's Advanced Distance Learning Network.

## Degree Requirements

### Materials Science & Engineering graduate courses (9 credits)

- MTE 510 Principles of Materials Science and Engineering
- MTE 525 Advanced Thermodynamics
- MTE 530 Crystallography, Diffraction and Microscopy of Materials
- MTE 540 Analytical Methods in Materials Engineering

- MTE 550 Phase Transformations in Materials
- MTE 560 Materials Performance and Reliability
- MTE 5842 Corrosion and Corrosion Control
- MTE 594P Analysis and Control of Materials Processes
- MTE 575/ME 4875 Introduction to Nanomaterials and Nanotechnology

### Manufacturing Engineering graduate courses (6 credits)

- MFE 510 Control and Monitoring of Manufacturing Processes
- MFE 520 Design and Analysis of Manufacturing
- MFE 530 Computer-Integrated Manufacturing
- MFE 540 Design for Manufacturability
- MFE 5841 Surface Metrology: Measurement and Analysis of Surface Textures
- MFE 594P Advanced Manufacturing Processes

### 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 above; 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.

## Project Description

After at least seven courses have been successfully completed, the student registers for the 3-credit project with one or more faculty advisors. The project, which is completed over a 14-week semester, should be identified by a materials processing company liaison. Ideally, the project is completed by a team of three; however, smaller or larger teams will be considered. Working with the liaison and faculty advisor, the team develops a clear statement of the goals and objectives of the project. Weekly meetings with the advisor and liaison including written and oral reports are required. The culmination of the project is a business plan and/or a research proposal or new product. The project should integrate the skills obtained and knowledge acquired in the student's coursework as well industrial experience.

## Faculty

**Richard D. Sisson, Jr.**, George F. Fuller Professor, Director of Manufacturing and Materials Engineering; Ph.D. Purdue University

**Y. K. Rong**, John Woodman Higgins Professor, Associate Director of Manufacturing and Materials Engineering; Ph.D., University of Kentucky

Faculty from Management, Manufacturing Engineering, Materials Science & Engineering and Mechanical Engineering work with this program. Also see those programs for complete faculty listings.

## Program of Study

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) and thermogravimetric 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 12.

## 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 credit hours. Requirements include the following six core courses: MTE 510, MTE 525, MTE 530, MTE 540, MTE 550, MTE 560, and two MTE or other 4000, 500 or 600 level engineering, science or mathematics electives, and 6 thesis credits. 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 weeks of the completion of the written exam. The MEDQE is offered 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.

All materials science and engineering students in the Ph.D. program must satisfactorily complete a minor in a program-related technical area. The minor normally consists of a minimum of three related courses and must be approved by the Graduate Study Committee and the program head.

# Materials Science and Engineering Laboratories and Research Centers

## Materials Characterization Laboratories

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. MCL is part of the Materials Science and Engineering Program, directed by Professor Richard D. Sisson, Jr. and managed by Professor Boquan Li. By using the lab, materials researchers can access major instruments in the area of electron microscopy (SEM, TEM), x-ray diffraction, optical microscopy (conventional and inverted), physical property determination (hardness and micro indentation hardness), and materials process (specimen preparation, heat treatment, metal evaporation and sputtering). All of the instruments are available for hands-on use by students and faculty. Licensed users have 24-hour access to the instruments. Training is available by appointment throughout the year. The MCL is also open to researchers from other universities and local industries.

## Nanomaterials and Nanomanufacturing Laboratory

This laboratory is well-equipped for advanced research in controlled nanofabrications 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. Device design, implementation, and test based on the obtained materials with improved quality will also be done in this laboratory.

## 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

The Surface Metrology Laboratory is dedicated to the study of surface textures, their creation and their influence of surface behavior or performance. We also study and design the manufacturing processes that create specific surface textures. We study and develop specialized algorithms that are used to support texture-related product and process design, and to advance the understanding of texture-dependent behavior. Our experience extends to analyzing data sets on scales from kilometers (earth's surface) to Angstroms (cleaved mica), although the primary focus is on analyzing measured surfaces or profiles (i.e., topographic data) acquired from surfaces created or modified during manufacture, wear, fracture or corrosion.

The objective of the research on texture analysis is to develop characterization parameters that reduce large data sets, such as those acquired by atomic probe microscopy, scanning profilometry, confocal microscopy, or conventional profilometry. The purpose of the characterization parameters is to support product and process design, or promote the understanding of adhesion, friction, wear, fracture, corrosion or other texture related phenomena.

## 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 creates 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 and the dissemination of new knowledge. More than 120 private manufacturers participate in the Institute, and their support helps fund

fundamental and applied research that addresses technological barriers facing the industry. The MPI researchers also develop and demonstrate best practices and state-of-the-art processing techniques.

MPI offers educational opportunities and corporate resources to both undergraduate and graduate students, specifically:

- International exchanges and internships with several leading universities around the globe—Europe and Asia
- Graduate internship programs leading to a master's or doctoral degree, where the research work is carried out at the industrial site

For further details visit the MPI office on the third floor of Washburn, Room 326, or the MPI Web site: [www.wpi.edu/+mpi](http://www.wpi.edu/+mpi).

MPI's research programs are carried out by three distinct research consortia. These are described below:

- Advanced Casting Research Center (ACRC)
- Center for Heat Treating Excellence (CHTE)
- Center for Resource Recovery & Recycling (CR3)

## Advanced Casting Research Center (ACRC)

The laboratory provides experimental facilities for course laboratories and for undergraduate and graduate projects. The laboratory is equipped with extensive melting and casting facilities, computerized data acquisition systems for solidification studies, thermal analysis units, liquid metal filtration apparatus, rheocasting machines, and a variety of heat treating furnaces. The laboratory has strong collaborations with industry, and students work directly with professional engineers from sponsoring companies. Forty corporate members participate in and support the ACRC research programs. Student scholarships offered by the Foundry Education Foundation (FEF) are available through the laboratory. The ACRC conducts work-shops, seminars and technical symposiums for national and local industries. The laboratory is available throughout the year for project activity and thesis work as well as co-op and summer employment. Project opportunities at international sites are also available through ACRC/MPI.

## Center for Heat Treating Excellence (CHTE)

The center is an alliance between the industrial sector and researchers to collaboratively address short-term and long-term needs of the heat treating industry. It is the center's intent to enhance the position of the heat treating industry by applying research to solve industrial problems, and to advance heat treatment technology. The center's objective is to advance the frontiers of thermal processing through fundamental research and development.

Specifically, the center will pursue research to develop innovative processes to:

- Control microstructure and properties of metallic components
- Reduce energy consumption
- Reduce process time
- Reduce production costs
- Achieve zero distortion
- Increase furnace efficiency
- Achieve zero emissions

Over 25 corporate members participate in and support the CHTE research programs. MPI project opportunities, industrial internships, coop opportunities and summer employment are available through CHTE/MPI.

## Center for Resources Recovery & Recycling (CR3)

The Materials Resource Recovery and Recycling I/UCRC center anticipates a future that values and increasingly strives to achieve materials sustainability. We are progressing towards a time when materials recovery and recycling are no longer an afterthought, but rather represent a critical consideration in the design and manufacture of materials and products. In the future, the efficiency of materials recovery from the waste stream will increase and recycled scrap will be the preferred input material for materials processes yielding both energy and cost saving.

## 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 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 tools and strategies, and
- 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.

## 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.

**Y. K. Rong**, John Woodman Higgins Professor; Associate Director, Manufacturing and Materials Engineering; Ph.D., University of Kentucky. CAD/CAM, manufacturing process and systems.

**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.

**D. Backman**, Research Professor of Mechanical Engineering; Massachusetts Institute of Technology. Materials modeling and simulation, design-materials integration, heat treatment, solidification processing, and aerospace materials and processes.

**I. Bar-On**, Professor; Ph.D., Hebrew University of Jerusalem. Mechanical behavior of materials, fracture and fatigue of metals, ceramics and composites, reliability and life 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; Director, Haas Technical Center; Ph.D., P.E., University of Vermont. Surface metrology, machining, fractal analysis, sports engineering, tribology, axiomatic design and abrasive processes.

**C. D. Demetry**, Associate Professor; Director of the Center for Educational Development and Assessment, Ph.D., Massachusetts Institute of Technology. Materials science and engineering education, nanocrystalline materials and nanocomposites, materials processing, and grain boundaries and interfaces in materials.

**T. El-Korchi**, Professor of Civil and Environmental Engineering, 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.

**R. N. Katz**, Research Professor; Ph.D., Massachusetts Institute of Technology. Ceramics Science and Technology, Failure Analysis, Design Brittle Material Technology Assessment, Mechanical Behavior of Ceramic & Metal Matrix Composites.

**D. A. Lados**, Assistant Professor of Mechanical Engineering; Director, Integrative Materials Design Center (iMdc); Ph.D., Worcester Polytechnic Institute. Fatigue, fatigue crack growth, and fracture behavior of materials - design and optimization for automotive, aerospace, marine, and military applications; microstructure characterization and microstructure-performance relationships; solidification and post-solidification processes (heat treatment) and impact on static and dynamic properties; material/process development; residual stress; plasticity; small and long crack growth behavior; fracture mechanics; fatigue life prediction models; powder metallurgy.

**B. Li**, Research Associate Professor; Manager of the Materials Characterization Laboratories; Ph.D., University of Science and Technology of China. Surface and interface physics, materials physics, growth and structural characterization of nanostructured materials, nanomaterials in energy storage and conversion applications, materials characterization, electron microscopy.

**J. Liang**, Assistant Professor, Ph.D., Brown University. Nanostructured materials, Materials Processing, nanomaterial Characterization.

**R. Ludwig**, Professor of Electrical and Computer Engineering, Ph.D., Colorado State University. Electromagnetic and acoustic Nondestructive Evaluation (NDE), electromagnetic/acoustic sensors, electromechanical device modeling, piezoelectric array transducers, numerical simulation, inverse and optimization methods for Magnetic Resonance Imaging (MRI).

**M. M. Makhlof**, Professor; Director, Aluminum Casting Research Laboratory; 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.

**S. Shivkumar**, Professor; Ph.D., Stevens Institute of Technology. Biomedical Materials, Plastics, Materials Processing.

**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.

## Course Descriptions

All courses are 3 credits unless otherwise noted.

### **MTE 510/ME 5310. Principles of Materials Science and Engineering**

This course provides a comprehensive review of the fundamental principles of materials science and engineering. The classical interplay among structure-processing-properties-performance in materials including plastics, metals, ceramics, glasses and composites will be emphasized. The structure in materials ranging from the subatomic 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. Basics of elasticity, plastic deformation and viscoelasticity will be highlighted. Salient aspects pertaining to the corrosion and environmental degradation of materials will be discussed. This course will provide the background for students in any engineering or science major for future course and research work in materials. (Prerequisites: senior or graduate standing in engineering or science.)

### **MTE/MFE 520. Design and Analysis of Manufacturing Processes**

The first half of the course covers the axiomatic design method applied to simultaneous product and process design for concurrent engineering, with emphasis on process and manufacturing tool design. Basic design principles as well as qualitative and quantitative methods of analysis of designs are developed. The second half of the course addresses methods of engineering analysis of manufacturing processes, to support machine tool and process design. Basic types of engineering analysis are applied to manufacturing situations including elasticity, plasticity, heat transfer, mechanics and cost analysis. Special attention will be given to the mechanics of machining (traditional, nontraditional and grinding) and the production of surfaces. Students, with the advice and consent of the professor, select the topic for their term project.

### **MTE 525/ME 5325. Advanced Thermodynamics**

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 chemical thermodynamics as well as heat engines. (Prerequisites: ES 3001, ME 4850 or equivalent.) Offered each year.

### **MTE 530/ME 5330. Crystallography, Diffraction and Microscopy of Materials**

The fundamentals of crystallography and X-ray diffraction of metals, ceramics and polymers will be presented and discussed. The techniques for the experimental determination of phase fraction and phase identification via X-ray diffraction will

be highlighted. The theory and practice of optical and electron microscopy will also be included. Both scanning and transmission electron microscopy will be theoretically and experimentally investigated. (Prerequisites: ES 200 or equivalent, and senior or graduate standing in engineering or science.)

### **MTE 540/ME 5340. Analytical Methods in Materials Engineering**

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 510 or equivalent.)

### **MTE 550/ME 5350. Phase Transformations in Materials**

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 510, ME 4850 or equivalent.)

### **MTE/ME/BME 554. Composites with Biomedical and Materials Applications**

Introduction to fiber/particulate reinforced, engineered and biologic materials. This course focuses on the elastic description and application of materials that are made up of a combination of submaterials, i.e., composites. Emphasis will be placed on the development of constitutive equations that define the mechanical behavior of a number of applications including biomaterial, tissue and materials science. (Prerequisites: Understanding of stress analysis and basic continuum mechanics.)

### **MTE 555/ME 4860. Food Engineering**

An introductory course on the structure, processing, and properties of food. Topics covered include: food structure and rheology, plant and animal tissues, texture, glass transition, gels, emulsions, micelles, food additives, food coloring, starches, baked goods, mechanical properties, elasticity, viscoelastic nature of food products, characteristics of food powders, fat eutectics, freezing and cooking of food, manufacturing processes, cereal processing, chocolate manufacture, micro-

bial growth, fermentation, transport phenomena in food processing, kinetics, preserving and packaging of food, testing of food. Recommended Background: ES 2001 or equivalent. This course will be offered in 2010-11 and in alternating years thereafter.

### **MTE 560/ME 5360. Materials Performance and Reliability**

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 will be discussed. A series of case studies will be used to illustrate the basic failure mechanisms of plastic deformation, creep, fracture, fatigue, wear and corrosion. 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.)

### **MTE 575/ME 4875. Introduction to Nanomaterials and Nanotechnology**

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 5815. Ceramics and Glasses for Engineering Applications**

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: ES 2001 or equivalent. This course will be offered in the fall of 2010.

### **MTE/MFE/ME 5841. Surface Metrology**

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 5842. Corrosion and Corrosion Control**

Advanced topics in corrosion. Stress corrosion cracking and hydrogen effects on metals. High-temperature oxidation, carburization and sulfidation. Discussions focus on current corrosive engineering problems and research. Course may be offered by special arrangement.

### **MTE 594. Special Topics**

As arranged

Theoretical or experimental studies in subjects of interest to graduate students in materials science and engineering. See the **SUPPLEMENT** section of the on-line catalog at [www.wpi.edu/+gradcat](http://www.wpi.edu/+gradcat) for descriptions of courses to be offered in this academic year.

### **Research**

As arranged

Additional acceptable courses, 4000 series, may be found in the Undergraduate Catalog.

## 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

This is an evening 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.

### 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.

## 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 bachelor's degree is required for admission to all M.S. programs. 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.

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 is a 30-credit-hour program. 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 560.

### For the M.S. in Applied Statistics

The master's program in applied statistics is a 30-credit-hour program. 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 professional M.S. Degree Program in Financial Mathematics is a 30-credit hour program. The curriculum consists of the following components:

### 1. 6 credits from required foundation courses:

MA 503 Analysis I or MA529 Stochastic Processes  
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 Management

### 3. 3 credits chosen from Mathematical Sciences graduate courses MA 502-590.

BS/MS students can count undergraduate credits MA 4213 Risk Theory, MA 4235 Mathematical Optimization, MA 4237 Probabilistic Methods in Operations Research, 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

BS/MS 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 MA579 Financial Programming Workshop

### 5. 3 graduate credits for a project originating in the financial industry 6. MA562A and MA562B Professional Master's Seminar (for no credit)

## For the M.S. in Industrial Mathematics

The professional master's degree program in industrial mathematics is a 30-credit-hour program. 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

A maximum of 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.

## 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 normally offered twice a year, once in January and once in August. A full-time student must make the first attempt within one year (two years for part-time students) of entering the Ph.D. program. Students entering with master's degrees are encouraged to take the GCE as early as they can.

### Mathematical Sciences Ph.D. Project

A student must 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.

## 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.

## 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](http://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.

## Faculty

**B. Vernescu**, Professor and Head; 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.

**J. Abraham**, Actuarial Mathematics Coordinator; Fellow, Society of Actuaries, 1991; B.S., University of Iowa, 1980.

**M. Blais**, Coordinator of Professional Science Master's Programs; Ph.D., Cornell University, 2005; mathematical finance.

**D. D. Berkey**, Professor and President; Ph.D., University of Cincinnati, 1974; applied mathematics, differential equations, optimal control.

**P. R. Christopher**, Professor; Ph.D., Clark University, 1982; graph theory, group theory, algebraic graph theory, combinatorics, linear algebra.

**S. Dai**, Visiting Assistant Professor; Ph.D., University of Maryland, 2005; Partial differential equations, pattern formation and domain coarsening in materials science, phase transitions and thin liquid films, free boundary problems, numerical analysis.

**P. W. Davis**, Professor; Ph.D., Rensselaer Polytechnic Institute, 1970; unit commitment, optimal power flow, economic dispatch, state estimation, other control and measurement problems for electric power networks.

**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).

**J. Goulet**, 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. Humi**, Professor; Ph.D., Weizmann Institute of Science, 1969; mathematical physics, applied mathematics and modeling, Lie groups, differential equations, numerical analysis, turbulence and chaos.

**C. J. Larsen**, Associate 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.

**W. J. Martin**, Associate Professor; Ph.D., University of Waterloo, 1992; algebraic combinatorics, applied combinatorics.

**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.

**J. D. Petrucci**, Professor; Ph.D., Purdue University, 1978; time series (nonlinear models), optimal topping (best choice problems), statistics.

**M. Sarkis**, Associate 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.

**H. Sayit**, Assistant Professor; Ph.D., Cornell University, 2005; stochastic optimization, stochastic differential equations, statistical estimation and inference, financial mathematics, computational finance.

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

**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.

**D. Vermes**, Associate Professor; Ph.D., University of Szeged, Hungary, 1975; optimal stochastic control theory, non-smooth analysis, stochastic processes with discontinuous dynamics, adaptive optimal control in medical decision making, massively parallel data analysis and simulation, portfolio risk management, financial mathematics.

**D. Volkov**, Assistant 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.

**S. Weekes**, Associate Professor and Associate Department Head; Ph.D., University of Michigan, 1995; numerical analysis, computational fluid dynamics, porous media flow, hyperbolic conservation laws, shock capturing schemes.

**Z. Wu**, Assistant Professor; Ph.D., Yale University, 2009; Biostatistics, high-dimensional model selection, linear and generalized linear modeling, statistical genetics, bioinformatics.

**V. Yakovlev**, Research Associate Professor; 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.

## **Emeritus**

**G. C. Branche**, Professor

**E. R. Buell**, Professor

**V. Connolly**, Professor

**W. J. Hardell**, Professor

**J. J. Malone**, Professor

**B. C. McQuarrie**, Professor

**W. B. Miller**, Professor

## Course Descriptions

All courses are 3 credits unless otherwise noted.

### Mathematical Sciences

#### 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 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  $\mathbb{R}^n$  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 is an introduction to modern numerical techniques. It is suitable for both mathematics majors and students from other departments. It covers material not treated in either MA 512 or MA 514, and it introduces the main ideas of those two courses. Topics covered may include interpolation by polynomials, roots of nonlinear equations, approximation by various types of polynomials, orthogonal polynomials, least-squares approximation, trigonometric polynomials and fast Fourier transforms, piecewise polynomials and splines, numerical differentiation and integration, unconstrained optimization including Newton's method and the conjugate direction method, and an introduction to the solution of systems of linear equations and initial value problems for ordinary differential equations. Both theory and practice are examined. Error estimates, rates of convergence and the consequences of finite precision arithmetic are also discussed. Other topics may include integral equations or an introduction to boundary value problems. In the course of analyzing some of the methods, topics from elementary functional analysis will be introduced. These include the concept of a function space, norms and inner products, operators and projections. (Prerequisite: knowledge of undergraduate linear algebra and differential equations, and a higher-level programming language is assumed.)

#### 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 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  $L^1$ ,  $L^2$ ,  $L^\infty$  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  $C^\infty$  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 ODEs and PDEs. Topics include spectral theory for linear operators in  $n$ -dimensional and infinite dimensional Hilbert spaces, spectral theory for symmetric compact operators, 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  $\mathbb{R}^n$ , 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 529 Stochastic Processes**

The objective of the course is to provide students with the foundations needed to model time-dependent random phenomena. 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 as partial differential equations or potential theory. The first half of the course consists of a rigorous review of measure theoretic probability with special emphasis on notions and tools needed to consider probability measures on spaces of functions. Topics include sigma algebras, probability measures, product measures, independence, integration, expectations, convergence theorems, filtrations, absolute continuity and conditional expectations. The second part of the course presents the core of the theory of stochastic processes and their applications. Topics include martingales, martingale convergence, stopping times, the construction and properties of the Brownian motion, the Ito integral and stochastic differential equations. The instructor may choose to include applications from physics, signal processing, finance, mathematical analysis or statistics. (Prerequisites: MA 503 or 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 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 ap-

plication 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 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 first 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 590. Special Topics**

Courses on special topics are offered under this number. Contact the Mathematical Sciences Department for current offerings. See the SUPPLEMENT section of the on-line catalog at [www.wpi.edu/+gradcat](http://www.wpi.edu/+gradcat) for descriptions of courses to be offered in this academic year.

### **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, inverse 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.

### **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.

### **MME 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.

### **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 queuing.

### **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  $\mathbb{Z}/n$ . 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**

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 pigeonhole 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 562. Seminar: Issues in Mathematics** 2 credits

This course gives students an opportunity to participate in focused discussions on various topics in mathematics and mathematics education. Students will research current literature in mathematics and mathematics education. Invited speakers will address issues relevant to a broad

understanding of mathematics and its applications in our society. Students will be required to synthesize and critique course materials through written papers and formal presentations. The course will emphasize teachers as professionals and educational innovators. The content of the course will vary depending on the interests of the participants. However, topics may include careers in mathematics; mathematics in industry; historical perspectives and the motivation of mathematical development; critical thinking skills; impact of the NCTM curriculum and evaluation standards; mathematics on the national scene, including the roles of MSEB, NSF, NCTM, AMS, MAA, AMATYC; mathematics reform: then and now; mathematics anxiety; issues in the teaching of developmental mathematics; women and minorities in mathematics; technical writing in mathematics; funding sources for mathematics reform; and assessment in mathematics, including the SAT, the AP Calculus Exam and ideas on alternative forms of assessment; textbooks and other resources in mathematics.

### **MME 592. 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. 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. 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 statistical 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.

## Programs of Study

The Mechanical Engineering Department offers two graduate degree options:

- Master of Science
- Doctor of Philosophy

## 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)
- 3 graduate credits in 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.

## 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	} 30 credits
Additional Dissertation Research (ME 699)	
Supplemental Research (ME 598, ME 698)	
<b>TOTAL</b>	<b>90 credits</b>

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	} 18 credits
Additional Dissertation Research (ME 699)	
Supplemental Research (ME 598, ME 698)	
<b>TOTAL</b>	<b>60 credits</b>

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 (ME591) 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. 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 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. 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 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.

## 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 two courses and a maximum of four courses may be counted toward both the undergraduate and graduate degrees. At least two must be 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.

The application for the B.S./Master's program must include a list of four 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 four courses listed for credit toward both the undergraduate and graduate degrees. However, admission is contingent upon the completion of two graduate courses (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.

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.

## Areas of Research and Areas of Study

Active areas of research in the Mechanical Engineering Department include: theoretical, numerical and experimental work in rarefied gas and plasma dynamics, electric propulsion, multiphase flows, turbulent flows, fluid-structure interactions, structural analysis, nonlinear dynamics and control, random vibrations, biomechanics and biomaterials, materials processing, mechanics of granular materials, laser holography, MEMS, computer-aided engineering systems, reconfigurable machine design, compliant mechanism design, and other areas of engineering design.

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 are parallel to the research interests of the mechanical engineering faculty. 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.

## Mechanical Engineering Laboratories and Centers

The Mechanical Engineering Department provides a multidisciplinary research and education environment combining elements of mechanical engineering, manufacturing engineering and materials science. The facilities are housed in the Higgins Laboratories and Washburn Shops.

### Aerodynamics Test Facility

The laboratory houses a low-speed, closed-return wind tunnel, with a test-section of 2' x 2' x 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.

### Biomechanics/Rehabilitation Engineering Laboratories

The Biomechanics and Rehabilitation Engineering Laboratories (HL 124, 127, 129) provide 2000 sq. ft. of modern laboratory space that supports courses with a focus on the design of assistive devices to aid persons with disabilities, biomechanics and biofluids Major Qualifying Projects (MQPs) and graduate student research. The laboratories also house the offices of the WPI Assistive Technology Resource Center and the WPI EPICS program (Engineering projects in Community Service). Major equipment includes a two-axis MTS Model 858 Mini Bionex testing machine, a benchtop tissue testing machine, a force plate and a hot wire anemometry system.

### Casting Laboratory

The Advanced Casting Research Center of MPI (WB 009) is a laboratory dedicated to research and development of advanced casting processes and to the improvement of currently practiced casting processes. The ACRC research facilities covers 1,637 sq. ft. and include a casting laboratory with induction and resistance melting furnaces, besides specialized heat treating furnaces. The laboratories are provided with modern instrumentation for research and

education in the field of materials science, such as mechanical properties facilities, metallographic equipment, thermal analyses (DTA and TGA), optical and electron microscopy facilities, and instrumentation for rheological characterization of metallic alloys in the semi-solid condition. Several workstations running commercial modeling packages are also available. These include Procast and Magma for simulation of casting processes and Thermocalc®, a thermodynamic simulation software widely used for undergraduate and graduate education in the field of materials science. At ACRC, WPI undergraduate students are offered unique learning opportunities through participation in actual research activities under supervision of graduate students and research staff members.

### **Center for Holographic Studies and Laser micro-mechatronics**

The laboratories of CHSLT cover over 2,800 sq. ft and are completely equipped and fully operational for educational and research activities. These activities range 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 the state-of-the-art equipment. This equipment includes several systems containing 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 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. Building off of these strengths, greatly diversified projects in a number of areas of current interest are being conducted using the Center's own unique and innovative methods.

### **Ceramic and Powder Processing Laboratory**

This laboratory and the one below cover a suite of five rooms that total almost 2,000 sq. ft. between WB337-342 of Washburn Shops. The lab is equipped with a variety of powder preparation, processing and characterization equipment, as well as equipment for green body consolidation and sintering. Equipment includes roller mills, mixers, a low temperature drying oven, freeze dryer, cold press, various sintering furnaces capable of up to 1700C in air and controlled atmospheres, a differential thermal analyzer, X-ray sedimentation, and equipment for electrical property and density measurements.

### **CNC Laboratory**

The CNC laboratory is located in the Washburn Shops Room 108 and covers 3,140 sq. ft. The focus 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. Originally the Haas machines included a VF3, a VFOE and the SL20, that were entrusted to WPI in 2001 were swapped out in July of 2004. They were again replaced in the Fall of 2007 with two new vertical machining centers and a new lathe: VF4, and VF2SS, both with 5 axis capabilities, and a TL15 with a sub spindle. Also included in the CNC Laboratory are a DoAll vertical knee mill, DoAll 13 manual lathe, Southbend tool room lathe, ordinary shop equipment and tooling (drill press, arbor press, stand grinder, etc.), along with a Starrett DCC CMM, Starrett Manual CMM, O.S. Walker Machining Magnet and a Hahn Engineering force-feedback grinder.

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.

### **Computational Fluid and Plasmadynamics Laboratory**

CFPL is a modern computational facility housed in HL236. It is used for graduate research and undergraduate projects in computational fluids, gas and plasma dynamics. The CFPL includes workstations, peripherals and data storage devices. CFPL has also a Linux cluster located in HL231, a specially designed computer facility. CFPL has access to Direct Simulation Monte Carlo, Particle-in-Cell, fluid dynamics, and MHD codes as well as visualization and data reduction software.

### **Control and Navigation of Multi-Vehicles Laboratory**

The CaN-MuVe Laboratory, a 400 square feet facility housed in HL312, focuses on the construction, testing, and development of autonomous multi-vehicle systems for exploration missions. Exploration includes the navigation and acoustic imaging of underwater environments using underwater vehicles, surface vessels, and ground robots.

The main project now underway in the laboratory is the construction of an autonomous underwater vehicle. All major vehicle electronics are available. These include a PC104-based computer core. It was chosen to handle the main processing requirements of the vehicle. The particular main board chosen is the Cheetah (made by VersaLogic), which is a 1.6 GHz Intel Pentium M equipped module that is 3.6" by 3.8". This microcomputer contains 1 GB of RAM, and 8GB solid state hard disk as well as a 60 GB spinning drive. Windows XP Embedded will be run on the processor. An analogue & digital input/output module for the PC104 bus is also available.

A 12 A brushless motor and an ElectriFly V-pitch propeller have been purchased for testing. Eight Groupner bow thrusters are also available for testing. Currently, a student group is working on the assembly and manufacturing of the thruster system, and the vehicle structure and body. The laboratory is equipped with a testing water tank, and the research group has permissions to use WPI's swimming pool for testing purposes.

The lab is also equipped with two iRobot Create systems (<http://www.irobot.com/create/explore/>) that include the iRobots, batteries, chargers, docks, command modules, virtual walls, BAMs, gumstix, wifistix, robostix and serial interface connector. This system is used to test cooperative coverage control algorithms developed by Prof. Hussein's research group.

The CaN-MuVe laboratory also has the following general purpose items: ATX power supply, a Quanser Q4 hardware in the loop board and a WinCon 5.0 real-time rapid control prototyping software.

### **Design Studio**

The Higgins Design Studio (HL 234) and the Computer Classroom (HL 230) are both part of the Keck Design Center on the second floor of Higgins Laboratories. Lecture/ laboratories in a variety of mechanical design and manufacturing courses are conducted in these labs. The labs are also available to students for general-purpose computational work on projects and coursework when not being used for instruction.

The 1600 sq. ft. Higgins Design Studio contains nineteen (19) high-end Linux workstations (Dell Precision, 2 Duo core CPUs, 4GB RAM, 24" Monitor) running software for mechanical design including parametric solid modeling (Pro/Engineer, Unigraphics, Ideas), structural, thermal, fluid and dynamic analysis (ANSYS, Abaqus, Nastran, Patran, Fluent, Comsol) and general purpose applications (Tectplot, Mathematica, MatLab, Maple). The Design Studio is connected to the campus network to allow for design collaboration through teleconferencing and exchange of design models to design partners and manufacturing facilities. Auxiliary equipment includes two laser printers and and 2 E-size color printer/plotter. In 2007-2008, the Design Studio supported ES3323 Advanced CAD (80-90 students) and ME3820 Computer-Aided Manufacturing (50-60 students). In addition, approximately 50 MQP teams and many Masters and PHD students utilized the lab. The lab is also the primary location for the new program in Scientific and Engineering software Applications training program.

The 1440 sq. ft. Computer Classroom contains forty (40) Windows XP Dell Optiplex 745 workstations (Intel E6300 Dual core CPU, 2GB of RAM, 20" monitor) and two laser printers. In addition to all of

the software available on the WPI campus network, locally installed software includes Solidworks, AutoCAD, Matlab, Maple, Mathcad, TK Solver, Thermal Analysis software and VisualStudio .Net.

### **Discovery Classroom and Laboratory**

The Discovery Classroom (HL 216) is an educational facility unique to WPI. In this 1,000 plus sq. ft. facility a state-of-the-art multimedia classroom is combined with an adjoining experimental laboratory to create an environment which emphasizes an integrated approach to engineering education. Classroom exercises, which combine analytical, computational, and experimental approaches in solving engineering problems, are made possible through this facility. For example, experiments can be set-up in a small portable wind tunnel in the Discovery Classroom Laboratory. The wind tunnel is then easily moved into the multi-media classroom for direct use in engineering lectures. Quantitative data from the wind tunnel experiments are immediately compared in-class to predictions from aerodynamic-based software, and to concurrently developed theory from lectures. The wind tunnel can then be moved back into the Discovery Classroom Laboratory for follow-up, hands-on laboratory exercises by the students. Other fluid dynamic and heat transfer apparatus such as a hydrodynamic bench, a laminar flow table, and heat transfer experiments (radial and axial conduction, forced convection, tube-in-tube heat exchangers, and radiation apparatus) are also housed in the laboratory, and used in a similar manner. The American Society of Engineers (ASME) has awarded WPI a national Curriculum Innovation Award – Honorable Mention in 2001 for this approach.

### **Fluid and Plasmadynamics Laboratory**

The FPL is located in HL314 and covers 500 sq. ft. It consists of several vacuum chambers and specialized test facilities for the investigation of onboard propulsion, electrospray sources (for both propulsion and nano-fabrication applications), plume/spacecraft interactions and microfluidics research. The laboratory includes an 18-inch diameter, 30-inch tall stainless steel vacuum chamber 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<sup>-6</sup> Torr range. This chamber is used primarily for study of electrospray sources.

For microfluidics research, FPL includes a calibrated flow system for delivery of liquid flowrates in the range of 75 – 250 micrograms/sec for studies of two phase flows in microchannels. Imaging of these flows is accomplished with a high-resolution monochrome progressive scan Pulnix-1325 camera with computer based image-capture and processing software. FPL includes a variety of tools and specialized instrumentation including oscilloscopes, precision source meter, electrometer and digital multimeters. Data from these instruments is collected and stored on computer using a LabView based data acquisition system.

### **Fluid Dynamics Laboratory**

This 400 sq. ft. laboratory is housed in HL 311. It is used for graduate 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 aerodynamic 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.

### **Heat Treating and Furnace Laboratory**

This laboratory (WB 345) is equipped with a variety of furnaces for the heat treatment of metals and ceramics. In addition, the CHTE quenching laboratory is housed in this space and is equipped with a variety of fully instrumented quench probes and data acquisition systems.

### **Intelligent Systems, Structures and Machines Laboratory**

The ISSM is a 400 sq. ft. facility housed in HL312, has state-of-the art data acquisition and control capabilities for experimental verification of control algorithms as applied to autonomous systems, intelligent machines and smart structures. Applications include structural, structural-acoustic, fluid-structure, thermal, thermoacoustic and mechatronics systems as applied in aerospace, mechanical, chemical and civil engineering.

Equipment include a dSPACE® ACE-1103 kit with DS1103 PPC Controller Board (8 analog outputs, 20 analog inputs, 6 encoder inputs), a dSPACE® ACE kit 1102 and two QUANSER® Hardware-in-The-loop Board with WinCon 4.1 Real-Time Control Software along with their dedicated PCs. To validate real-time vibration control experiments the ISSM lab has a TMC® active vibration isolation table (TMC® model 63-563), four single-channel ACX®-EL1224 high voltage/low amps power amplifiers, one double-channel Krohn-hite® (model 7602M) power amplifier, one six-channel rack mounted PCB® (model 790A06) power amplifier for piezoceramic patch actuation and an HP dynamic signal analyzer (model 35665A). Five BK precision® (model 1761) power supplies and a Kepco® power supply (model ATE 55-10DM) are available to provide a range of power supply requirements, and five BK precision® (model 5492) digital multimeters are available for testing of electronic components.

Acceleration, velocity and strain measurements, are made possible via accelerometers. ISSM has five miniature (0.5g) ceramic shear ICP accelerometers (PCB® model U352C22), a four-channel PCB® signal conditioner (model 442C04) with gain 1x, 10x, 100x, and one PCB® dual-mode vibration amplifier (velocity or position) single channel (model 443B01). A PCB® ICP microphone is also available for pressure measurements.

For calibration and signal conditioning, ISSM has a Krohn-hite® Low-Pass/High-Pass Butterworth/Bessel 4-Channel Filter (model 3364), a PCB® handheld shaker for accelerometer calibration, a 4-channel PCB® line-powered sensor signal conditioner with gain 1x, 10x and 100x, one PCB® modally tuned Impact Hammer kit for vibration testing, and one dual-mode PCB® vibration amplifier (velocity or position) single-channel (model 443B101). In addition, ISSM has an Agilent® 20Mhz Function/Arbitrary waveform generator (model 33220A) and dedicated workstations for control design and implementation accessing Matlab®'s Real-Time Workshop, Optimization, Linear Matrix Inequalities and Robust Control toolboxes.

In addition, the ISSM lab has seven iRobot® Create programmable robots equipped each with a bluetooth adapter module (BAM) for complete wireless

control and their own advanced power system batteries. A bluetooth USB radio provide remote communication with the iRobot® Create programmable robot and the BAM. This wireless mobile sensor network is used for verification of moving source detection schemes as applied to biochemical source detection and containment, and intrusion detection in enclosed spaces. Added to these mobile robots, is an autonomous battery-powered helicopter equipped with its own IMU unit and has the ability to communicate with the iRobot® mobile sensor network in order to create a heterogeneous sensor network.

### **Mechanical Aerospace Engineering Controls Laboratory**

The MAEC lab is located in an 880 sq. ft. facility in HL 248 and serves the experimental component of the controls and advanced dynamics courses. It has four stations each equipped with a dSPACE ACE 1104 kit with DS1104 R&D Controller Board, an Instek® function generator (model CFG-8219A), a Comdyna (GP-6) analog computer and a Tektronix (model TDS2012) digital storage oscilloscope.

### **Mechanical Energy and Power Systems Laboratory**

The Mechanical Energy and Power Systems Laboratory (HL 124) provides 700 sq. ft. of modern laboratory space for research towards improving the efficiency of energy generation, transfer, and storage. The laboratory is equipped with data acquisition equipment, a hydraulic test stand, prototyping parts and equipment, mechanical and electrical tools, power supplies, sensors, and meters. The facility is equipped with a fume hood, compressed air, vacuum, water, and 220 VAC power.

### **Mechanical Testing Laboratory**

The 1,497 sq. ft. Mechanical Testing Laboratory (WB 113) has three state-of-the art Instron materials test systems. They are Instron 8502, Instron 8511, and Instron 5500 with an Instron environmental chamber. The three systems can be used to evaluate the mechanical properties and performance of metals, plastics, composites, textiles, ceramics, rubber, biomedical, and adhesives.

The two 8500 series servo-hydraulic testing systems are designed for use in dynamic/fatigue testing of a wide range

of materials and components. They can apply loads to the specimen in the range of up to +/- 250 kN. Test specimens can be cycled from very low rates to frequencies as high as 200 Hz or more. Displacement amplitudes range from a few micro-meters to over 250 mm. Specifically, the Fast-Track™ 8800™ Digital Controller with multi-axis fatigue testing capabilities and high performance HS488 GPIB interface, offers an expandable architecture ideal for the most demanding applications. Additionally, high speed, digital electronics provide the tight, continuously self-correcting action required to assure the controlled parameter conforms precisely to the desired test program.

The Instron 5500 testing system provides comprehensive, versatile solutions for the broadest range of materials testing requirements. It features advanced digital electronics, combined with robust load frames and drive systems, to provide high accuracy and reliable performance. The system utilizes important safety features and innovative test and control software to make even the most complex testing applications easy to set up and operate.

The Instron environmental chamber provides advanced high/low temperature and environmental systems. It features special window design to ensure optimal performance from Instron's optical extensometers, and covers a temperature range from -150 to 600°C (-240 to 1110°F). It is designed for use in both static and dynamic testing of a wide range of materials and components including plastics, metals, elastomers, paper, textiles and composites.

### **MEMS Fabrication Laboratory**

The MEMS Fabrication Laboratory is located on the ground floor in the Higgins Laboratory.

This state-of-the-art process facility has been developed as a center of excellence in device technologies for silicon and various compound semiconductor materials. The facility will cover education and research in areas of microelectronics, optoelectronics, integrated sensors, and MEMS technology based devices.

The MEMS Fabrication Laboratory is a Class 100 facility with approximately 500 square feet of floor space, including the gowning area. It is equipped with instrumentations to support photolithography,

thermal deposition and oxidation, wet chemistry, metrology, and wafer bonding. The MEMS Fabrication Laboratory has, in place, protocols for handling a broad range of chemicals and gases.

A separate, but contiguous, research laboratory has characterization facilities that include microscopy, profilometry, and optoelectronic holography (OEH). Further characterization facilities are available through the laboratories using SEM, AFM, and X-Ray Diffraction that provide necessary metrology capabilities for the devices that are fabricated.

The MEMS Fabrication Laboratory is one of the most secure laboratories on campus and has the capability to serve a diverse community of users and research disciplines.

### **Microflow Laboratory**

This 400 sq. ft. laboratory is housed in HL311. It consists of a vacuum chamber and specialized equipment for the investigation of gaseous and plasma microflows, with application to microsensors, microdevices, and micropropulsion. The laboratory includes an 18-inch diameter, 30-inch tall stainless steel vacuum chamber. The MFL includes a variety of tools and specialized instrumentation including oscilloscopes, precision source meter, electrometer and digital multimeters.

### **Nanofabrication and Nanomanufacturing Laboratory**

This new laboratory located in the Washburn Shops (WB337) is equipped with facilities for advanced research in the areas of bottom-up nanofabrication through uniform self-assembly, nano-bioscience, and characterization of nanomaterials and biomaterials.

The 558 sq. ft. laboratory is furnished with the following equipment: Anodization, electrodeposition, electroless deposition workstations, a chemical vapor deposition system, Fisher Scientific Iso-temp tissue culture incubator, UV-visible spectrophotometer, BAS electrochemical workstation, Millipore filtration system, Standard equipment to synthesize and process nanomaterials and biomaterials such as a chemical fume hood, a water purification system, an analytical balance, a micro centrifuge, low temperature storage, water baths, stirring hotplates, a pH meter, a ultrasonic cleaner, and a programmable heavy duty muffle furnace.

The research carried out in the laboratory includes; Fabrication of highly-ordered nanomaterials, such as metal nanowires, metal and ceramic nanodots, carbon nanotubes, protein nanotubes, and organic-ceramic nanocomposites; Investigation of the cell-nanostructured substrata interactions to understand how nanostructured extracellular matrix molecules regulate cell growth and differentiation; Study of the mechanical, thermal, electrical and optical properties of uniform and complex nanomaterials for novel applications.

### **Optical and Electron Metallography Laboratories**

The Materials Characterization Laboratory (MCL) includes 327 sq. ft. housed in HL047 offers a range of analytical techniques in the area of electron microscopy (JEOL 7000F LV and JEOL 840 scanning electron microscopes, and JEOL 100 CXII transmission electron microscope), x-ray diffraction (GE-XRD-5 diffractometer), and optical microscopy (conventional and inverted), physical property determination (hardness and micro indentation hardness), and materials processing (specimen preparation, heat treatment, metal evaporation and sputtering).

The JEOL-7000F thermal field-emission gun SEM (HL047) has a unique in-the-lens TFEG design, enabling high probe current at lower voltage in a small spot size. It is equipped with an Oxford Energy 250 Energy Dispersive X-ray Microanalysis System with Analytical Drift Detector. The high probe current and the high x-ray detection efficiency of the Analytical Drift Detector make the routine analytical work much faster. The JEOL-840 (WB245) is a general purpose high-performance, low cost scanning electron microscope with excellent Secondary Electron Imaging and Backscattered Electron Imaging resolution. The specimen chamber can accommodate a specimen of up to 100 mm in diameter. The 840 SEM is equipped with Kevex energy dispersive x-ray spectroscopy system, making it suitable for microstructural and chemical analysis of advanced materials.

The JEOL-100CXII (WB248) is a conventional TEM, optimized for diffraction contrast imaging and electron diffraction studies. It operates at energy up to 100kV. A double tilt holder is available with  $\pm 60$  degrees of X tilt and  $\pm 36$  degrees of Y tilt. The TEM is used for micro-

structural and crystallographic studies of a wide variety of materials including metal alloys, polymers, nanostructured materials, and biomaterials.

The GE-XRD-5 diffractometer (WB231) is a polycrystalline diffraction system, which can be used for crystal structure determination, precise lattice parameter measurements, phase diagram determination, determination of crystalline size and strain, quantitative analysis of powder mixtures, and residual stress analysis. A variety of software, including background modeling, peak searching, curve fitting et al and x-ray tube targets are available to provide a wide x-ray analysis capability.

A suite of optical microscopes (WB245, 342) are available for microstructural characterization needs, which include one Nikon EPIHOT inverted microscope with a Nikon Digital Sight DS-U1 digital image collecting system, two aus JENA inverted microscopes, three Nikon conventional optical microscopes, one Leitz Metallux II conventional microscope, and one Unitron ME-1510 microscope.

Three Rockwell hardness testers, one Shimadzu HMV-2000 digital microindentation hardness tester, and a Buehler MMT-3 digital microindentation hardness tester (WB342) are available for hardness evaluation of materials from soft Al alloys to hard steel and ceramics.

A full set of specimen preparation tools are available. These include cutting, slicing, mounting, grinding and polishing. The available machines including one Buehler 12" wheel cut-off machine, two Mark V CS600 cutters(WB253), two Buehler Isomet 11-1180 low speed saw(WB341), two Buehler Simplimet II mounting presses(WB253), one Buehler EcometIV automatic grinder-polisher, two Buehler Metaserv 2000 grinder-polishers, three Ecomet 5 two-speed grinder-polishers, 3 Century E-plus grinder-polisher, three Buehler Vibromet I polishers, and one Buehler Electromet 4 polisher-etcher(WB341).

### **Polymer Engineering Laboratory**

The equipment include Perkin Elmer Thermal Analysis systems Model DSC4, DSC7, DTA1400, and TGA7; single screw tabletop extruder, injection molding facilities, polymer synthesis apparatuses, oil bath furnaces, heat treating ovens, and foam processing and testing devices.

## Robotics Laboratory

The Robotics Laboratory, a 1,915 sq. ft. facility, is located on the first floor of the Washburn Building (WB107). It 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 and graduate researchers. In addition to a small manual milling area, the two largest CNC milling machines in the Haas Technical Center are housed in the Robotics Laboratory. Students working in groups and under the supervision of the lab manager regularly perform complex project machine work using both the manual and CNC machine tools.

**Industrial Robots:** The robots in the laboratory include: two Fanuc A510b SCARA robots with RH controls, two Adept One SCARA robots with VALII controls, one Puma 761 Clean Room edition six axis jointed robot with a Unimate controller, and one Asea IRB60.

## Surface Metrology Laboratory

This laboratory is located in WB243 and covers 153 sq. ft. The lab is dedicated to advancing the understanding of the formation, behavior, measurement and analysis of surface roughness. The lab has pioneered technological development and industrial applications of scale-sensitive fractal analyses, a method invented and patented by Prof. Brown and co-workers. The lab has studied a broad range of surfaces including hard drives, cutting tools, skin, teeth, food, rocks, skis, pills, pavements, tires, bullets, and industrial diamonds. The lab has developed advanced techniques for differentiating surfaces based on texture measurements and for finding the scales at which the differentiation can be made.

Graduate and students typically work together on a variety of projects. Recent projects include characterizing scratches on teeth supported by the NSF, surface of pill compacts supported by Pfizer, fractography of chocolate, and the structure of ground ski bases. Current projects include the measurement of paper, granite, skin, teeth, works of art, and grinding wheels, and the determination of uncertainty, and noise control and management in surface measurements.

## Vacuum Test Facility (VTF)

Also located in the Aerospace Laboratory is the Vacuum Test Facility (VTF). The VTF is designed to support ongoing research and educational activities requiring a controlled vacuum environment. The cornerstone of this facility is a 50 in diameter, 72 in long stainless steel vacuum chamber which will enable the creation of a vacuum environment for use in the characterization of electric and chemical thruster performance, investigation of neutral and ionized gas plume expansion in a vacuum, and testing of avionics for nanosatellites designed to operate in a vacuum environment.

The pumping system for the VTF 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, the mechanical pump would be used initially to pump the system down to the milli-Torr pressure range. Pumping would then transition to a 20" cryopump which can provide up to 10,000 liters/s (on N<sub>2</sub>) at pressures less than 10<sup>-6</sup> Torr.

## Faculty

**Gretar Tryggvason**, Professor, Department Head; Ph.D., Brown University, 1985; Numerical modeling of multiphase flows

**Diran Apelian**, Howmet Professor, Director of the Metals Processing Institute; Sc.D., Massachusetts Institute of Technology, 1971; Solidification processing, spray casting, molten metal processing, aluminum foundry processing, plasma processing and knowledge engineering in materials processing

**Holly K. Ault**, Associate Professor; Ph.D., Worcester Polytechnic Institute, 1988; Geometric modeling, mechanical design, CAD, kinematics, biomechanics and rehabilitation engineering

**Daniel Backman**, Research Professor, Sc.D., Massachusetts Institute of Technology, 1975; Materials modeling, solidification, and aerospace materials and processes

**Isa 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

**John 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

**Christopher A. Brown**, Professor; Ph.D., University of Vermont, 1983; Surface metrology, machining, grinding, mechanics of skiing, axiomatic design

**Eben C. Cobb**, Visiting Assistant Professor; Ph.D., University of Connecticut, 1985; Computer aided design and kinematics, robotics, dynamics of high-speed rotating equipment, smart structures, vibration control

**Michael A. Demetriou**, Associate 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

**Chrysanthe 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

**Mikhail F. Dimentberg**, Professor; Ph.D., Moscow Institute of Power Engineering, 1963; Applied mechanics, random vibrations, nonlinear dynamics, rotordynamics, mechanical signature analysis, stochastic mechanics.

**Simon Evans**, Assistant Professor, Ph.D., Cambridge University, UK, 2009; Fluid mechanics and turbomachinery, flow control

**Gregory Fischer**, Assistant Professor, Ph.D., Johns Hopkins University, 2008; Medical robotics, computer assisted surgery, robot control, automation, sensors and actuators

**Mustapha S. Fofana**, Associate Professor; Ph.D., University of Waterloo, Waterloo, Canada, 1993; Delay dynamical systems, nonlinear machine-tool chatter, stochastic nonlinear dynamics, reliability dynamics and control of medical ambulance, design and manufacturing of combat feeding systems, CNC machining dynamics and control, and sustainable lean manufacturing systems.

**Cosme Furlong**, Assistant Professor; Ph.D., WPI, 1999; MEMS and MOEMS, nanotechnology, mechatronics, laser applications, holography, computer modeling of dynamic systems

**Nikolaos A. Gatsonis**, George I. Alden Professor, Director, Aerospace Engineering Program, Associate Department Head; 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

**John (Jack) R. Hall**, Adjunct Professor; Ph.D., University of Florida, 1962; Dynamic signal analysis, vibration analysis, engineering instrumentation

**Allen H. Hoffman**, Professor; Ph.D., University of Colorado, 1970; Biomechanics, biomaterials, biomedical engineering, rehabilitation engineering, biofluids and continuum mechanics

**Zhikun 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

**Islam I. Hussein**, Assistant Professor; Ph.D., University of Michigan, 2005; Cooperative control of intelligent multiple vehicle sensor network systems, geometric mechanics and control, and optimal control theory

**Robert N. Katz**, Research Professor; Ph.D., Massachusetts Institute of Technology, 1969; Materials science, ceramics, metal matrix composites, technology assessment, design with brittle materials, materials processing

**Diana Lados**, Assistant Professor; Ph.D., Worcester Polytechnic Institute, 2004; Design and optimization of materials for fatigue, fatigue crack growth, and fracture resistance, fracture mechanics, residual stress, plasticity, solidification

**Jianyu Liang**, Assistant 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 nanopatterned substrates for electronic, optic, and biomedical applications

**Jiacai Lu**, Research Assistant Professor; Ph.D., Xi'an Jiaotong University, Xi'an, P.R. China, 1999; Numerical modeling of multiphase flows

**Makhlouf 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

**Stephen S. Nestinger**, Assistant Professor, Ph.D., University of California, Davis, 2009; Intelligent mechatronic and embedded systems and their applications

**Robert L. Norton**, Milton Prince Higgins II; M.S., Tufts University, 1970; Mechanical design and analysis, dynamic signal analysis, computer-aided engineering, computer-aided design, finite element method, vibration analysis, engineering design, biomedical engineering

**David J. Olinger**, Associate Professor; Ph.D., Yale University, 1990; Fluid mechanics, aero- and hydrodynamics, fluid structure interaction, fluid flow control, renewable energy

**Ryszard J. Pryputniewicz**, K. G. Merriman Professor; Ph.D., University of Connecticut, 1976; MEMS and nanotechnology, laser applications, holography, fiber optics, computer modeling of dynamic systems, bioengineering

**Mark W. Richman**, Associate Professor, Graduate Committee Chair; Ph.D., Cornell University, 1984; Mechanics of granular flows, powder compaction, powder metallurgy

**Yiming (Kevin) Rong**, John Woodman Higgins Professor and Associate Director Manufacturing & Materials Engineering; Ph.D., University of Kentucky, 1989; Manufacturing systems and processes, heat treatment process modeling and simulation, CAD/CAM, computer-aided fixture design and verification

**Brian J. Savilonis**, Professor; Ph.D., State University of New York at Buffalo, 1976; Thermofluids, biofluids and biomechanics, energy, fire modeling

**Satya S. Shivkumar**, Professor; Ph.D., Stevens Institute of Technology 1987; Plastics, materials science and engineering, biomaterials, food engineering

**Richard D. Sisson, Jr.**, George F. Fuller Professor; Ph.D., Purdue University, 1975; Materials process modeling and control, manufacturing engineering, corrosion, environmental effects on metals and ceramics

**John M. Sullivan, Jr.**, Professor; 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

**James D. Van de Ven**, Assistant Professor; Ph.D., University of Minnesota, 2006; Applying machine design to the areas of efficient energy conversion and storage, automotive engineering and fluid power

## Course Descriptions

All courses are 3 credits unless otherwise noted.

### ME 500. Applied Analytical Methods

The emphasis of this course is on the modeling of physical phenomena encountered in mechanical engineering, 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 and numerical techniques as they are required to study such phenomena. Depending on the examples chosen, the techniques covered may include ordinary differential equations, partial differential equations, Fourier series, transform methods, linear algebra, multivariable and vector calculus, calculus of variations, and numerical simulations.

## Fluids Engineering

### ME 511. Incompressible Fluid Dynamics

An introduction to graduate level fluid dynamics including dimensional analysis, Eulerian and Lagrangian descriptions, flowlines, conservation equations, governing equations of viscous fluid motion, exact solutions of Navier-Stokes and Euler equations, unsteady flows, laminar boundary layer theory, turbulence, separation, Stokes flow, vorticity dynamics, potential flow and surface flows. (Prerequisites: Fundamentals of thermo-dynamics and mechanics, knowledge of advanced mathematics, undergraduate courses in fluid mechanics.)

### ME 512. Gas Dynamics and Real Gas Effects

Kinetic theory of gases including equilibrium and nonequilibrium gas properties, macroscopic equations, binary and inelastic collisions, chemical reactions. Equilibrium flows including steady and unsteady shock waves, nozzle flow, Prandtl-Meyer flow, theory of characteristics, effects of head addition and friction, linearized compressible flow and acoustics. Compressible flows with vibrational, chemical or translational nonequilibrium including variable transport properties, nozzle flow and shock waves. (Prerequisites: Background in fluid dynamics (incompressible and compressible), thermodynamics, and basic undergraduate physics and chemistry.)

### ME 513. Thermodynamics

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 515. Computational Methods for PDEs in Engineering Science

This course is devoted to the numerical solution of partial differential equations encountered in engineering sciences. Finite difference and finite element methods are introduced and developed in a logical progression of complexity. 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.

### ME 516. Heat Transfer

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 611. Turbulence

Material to be covered: introduction and motivation, statistical techniques for analysis, mean flow dynamics (Reynolds decomposition), Kolmogorov's theory, instrumentation, classical turbulent flows—shear layers, jets, wakes, boundary layers—and pipe flow. (Prerequisites: Fundamentals of mechanics and thermodynamics, graduate level course in fluid mechanics and knowledge of advanced mathematics.)

### ME 612. Computational Fluid Dynamics

Computational methods for incompressible and compressible viscous flows. Navier Stokes equations in general coordinates and grid generation techniques. Finite volume techniques including discretization, stability analysis, artificial viscosity, explicit and implicit methods, flux-vector splitting, TVD schemes and multigrid methods. Finite elements. Concepts of vectorization and parallel computing. Applications are drawn from internal, external flows, materials processing. (Prerequisite: Fluid dynamics and introductory course in numerical methods.)

## Dynamics and Controls

### ME 522. Mechanical Vibrations

Vibration analysis for both discrete and continuous linear systems. Start with an enhanced review of the fundamentals of single-degree-of-freedom vibration analysis. Both Newton-D'Alembert's vectorial approach and Lagrangian equations are discussed. General properties of related stiffness, mass and damping matrices are addressed. Modal analysis for linear systems is emphasized. Computational methods in vibration analysis are introduced. Applications include vehicles traveling on a rough surface, multistory buildings subjected to seismic and wind loading, and vibration analysis of bars, beams and plates.

### ME 523. Applied Linear Control

Modeling of complex systems used in various areas of engineering. Analytical description of dynamic physical systems, time and frequency domain representations. System characteristics such as controllability, observability and stability. Design of feedback controllers using state-space methods including pole placement and optimal control. State observers and introduction to Kalman filters. Performance limitation of control systems and trade-offs in control design. Design of control synthesis is performed using Matlab/Simulink. Term projects focus on design, analysis and implementation of current engineering control problems. (Prerequisites: Differential equation and fundamentals of linear algebra.)

### ME 527. Dynamics

Basic concepts and general principles of classical kinematics and dynamics of particles, system of particles, and rigid and deformable bodies are presented. Particle motion along arbitrary trajectories is discussed in general coordinate systems. The governing equations of motion are derived by both Newton-D'Alembert's vectorial approach and Lagrange-Hamilton's variational approach. Applications include central-force orbital motion, binary collisions, motion in noninertial reference frames, rigid body motion, vibration of continuous systems and dynamic stability.

### ME 621. Dynamics and Signal Analysis

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.

### ME 622. Advanced Dynamics and Vibrations

The course presents advanced topics in dynamics and vibrations of machines and structures. Depending on the instructor, the course will include a selection of the following topics: extended discussion of vibration analysis of linear systems with distributed parameters, an introduction to vibration of nonlinear systems, numerical methods for vibration analysis, random vibrations, stability of dynamic systems, flow induced vibrations and rotordynamics.

### ME 623. Applied Nonlinear Control

Introduction to the analysis and design of nonlinear control systems. Stability analysis using Lyapunov, input-output and asymptotic methods. Design of stabilizing controllers using a variety of methods: linearization, absolute stability, sliding modes, adaptive, and feedback linearization. Applications include control design for robot systems (position and trajectory control), flexible structures (vibration control), spacecraft attitude control, manufacturing systems. Case studies for systems with smart actuators/sensors (Piezo, SMA, Magnetostrictive), deadzones and hysteresis, etc. Design of control synthesis is performed using Matlab/Simulink. Term projects will focus on design, analysis and implementation of current engineering control problems. (Prerequisites: Differential equations and fundamentals of linear algebra.)

## Structures and Materials

### ME 531. Applied Elasticity

This course is intended for students with undergraduate backgrounds in mechanics of materials. It includes two- and three-dimensional states of stress, linear and nonlinear measures of strain, and generalized Hooke's Law. Also covered are exact solutions for bending and torsion: thick-walled pressure vessels, rotating disks, stress functions for two- and three-dimensional problems and bending and torsion of unsymmetric beams.

### ME 5310/MTE 510. Principles of Materials Science and Engineering

This course provides a comprehensive review of the fundamental principles of materials science and engineering. The classical interplay among structure-processing-properties-performance in materials including plastics, metals, ceramics,

glasses and composites will be emphasized. The structure in materials ranging from the subatomic 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. Basics of elasticity, plastic deformation and viscoelasticity will be highlighted. Salient aspects pertaining to the corrosion and environmental degradation of materials will be discussed. This course will provide the background for students in any engineering or science major for future course and research work in materials. (Prerequisites: senior or graduate standing in engineering or science.) Offered each year.

### **ME 5325/MTE 525. Advanced Thermodynamics**

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 chemical thermodynamics as well as heat engines. (Prerequisites: ES 3001, ME 4850 or equivalent.) Offered each year.

### **ME 533/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.)

### **ME 534. Laser Engineering Science and Applications**

In this course, a unified account of the present-day knowledge of lasers and their applications in varied professional and industrial fields will be given through a series of in-class lectures and laboratory demonstration. Special attention will be given to factors that must be evaluated when a laser system is being devised for a specific application. Course coverage will include types of lasers and their characteristics, shaping of laser beams, measurement of laser beam parameters, transmission of laser beams, interaction of laser beams with materials, mathematical modeling of laser processes, laser processing of materials, fiber-optic applications of lasers, laser metrology and related topics.

### **ME 5327/CE 527. Impact Strength of Materials**

This course provides the student with a basic understanding of the mechanics of impact and contact as well as the behavior of materials subjected to dynamic loadings. Topics will include elastic and plastic stress waves in rods; longitudinal, torsional and flexure waves; shock waves; impulsively loaded beams and plates; impact of rough bodies in three dimensions, impact of bodies with compliance, impact of slender deformable rods, continuum modeling of contact regions and progressive collapse of structures.

### **ME 5329/CE 529. Impact Finite Element Analysis**

Modern practical contact/impact problems like the design of automobiles, aircraft, ships packaging, etc. depend on the use of nonlinear dynamic large-deformation high-strain rate explicit finite element computer programs. The purpose of this course is to provide the student with background sufficient for them to understand the workings of such programs and the ability to use such program to build models and perform analyses of contact/impact problems. Topics will include explicit time integration, penalty and constraint contact methods, under-integrated element formulations, hourglass control, developing finite element models and performing and interpreting finite element analysis results.

### **ME 5330/MTE 530. Crystallography, Diffraction and Microscopy of Materials**

The fundamentals of crystallography and X-ray diffraction of metals, ceramics and polymers will be presented and discussed. The techniques for the experimental determination of phase fraction and phase identification via X-ray diffraction will be highlighted. The theory and practice of optical and electron microscopy will also be included. Both scanning and transmission electron microscopy will be theoretically and experimentally investigated. (Prerequisites: ES 200 or equivalent, and senior or graduate standing in engineering or science.) Offered each year.

### **ME 5340/MTE 540. Analytical Methods in Materials Engineering**

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 510 or equivalent.) Offered each year.

### **ME 5350/MTE 550. Phase Transformations in Materials**

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 510, ME 4850 or equivalent.) Offered each year.

### **ME 5360/MTE 560. Materials Performance and Reliability**

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 will be discussed. A series of case studies will be used to illustrate the basic failure mechanisms of plastic deformation, creep, fracture, fatigue, wear and corrosion. 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.) Offered each year.

### **ME/MTE/MFE 5841. Surface Metrology**

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 634. Holographic Numerical Analysis**

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.)

## **Manufacturing and Design**

### **ME 542/MFE 510. Control and Monitoring of Manufacturing Processes**

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.

### **ME 543/MFE 520. Design and Analysis of Manufacturing Processes**

The first half of the course covers the axiomatic design method, applied to simultaneous product and process design for concurrent engineering, with the emphasis on process and manufacturing tool design. Basic design principles as well as qualitative and quantitative methods of analysis of designs are developed. The second half of the course addresses methods of engineering analysis of manufacturing processes, to support machine tool and process design. Basic types of engineering analysis are applied to manufacturing situations, including elasticity, plasticity, heat transfer, mechanics and cost analysis. Special attention will be given to the mechanics of machining (traditional, nontraditional and grinding) and the production of surfaces. Students, with the advice and consent of the professor, select the topic for their term project.

### **ME 544/MFE 530. Computer-Integrated Manufacturing**

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.

### **ME 545. Computer-Aided Design and Geometric Modeling**

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, Boolean algebra and solid modeling, transformations, computational and

analytic geometry, automatic mesh generation, tool path generation, 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, computer programming, and some familiarity with a CAD system.)

### **ME 641. Cam Design**

Basic and advanced methods of cam design for high-speed production machinery and automotive applications will be addressed. Classical as well as polynomial and spline-based methods will be used to design cam contours. Issues of cam manufacturing and vibrations as related to cam dynamic behavior will be discussed. Practical aspects of cam design will be exercised through projects and laboratory assignments. (Recommended background: Undergraduate level courses in kinematics and vibrations. Familiarity with the techniques of dynamic signal analysis [ME 621] would be helpful.)

## **Biomechanical Engineering**

### **ME/BME 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. (Recommended preparation: A first course in biomaterials equivalent to ME/BME 4814 and a basic understanding of physiology and cell biology.)

### **ME/BME 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. (Recommended preparation: A first course in biomechanics equivalent to ME/BME 4504.)

### **ME/MTE/BME 554. Composites with Biomedical and Materials Applications**

Introduction to fiber/particulate reinforced, engineered and biologic materials. This course focuses on the elastic description and application of materials that are made up of a combination of submaterials, i.e., composites. Emphasis will be placed on the development of constitutive equations that define mechanical behavior of a number of applications including: biomaterial, tissue, and material science. (Prerequisites: Understanding of stress analysis and basic continuum mechanics.)

### **ME/BME 558. Biofluids and Biotransport**

The emphasis of this course is on modeling fluid flow within the cardiovascular and pulmonary systems, and the transport processes that take place in these systems. Applications include artificial heart valves, atherosclerosis, arterial impedance matching, clinical diagnosis, respiration, aerosol and particle deposition. Depending upon class interest, additional topics may include reproductive fluids, animal propulsion in air and water, and viscoelastic testing. (Recommended preparation: A first course in biofluids equivalent to ME/BME 4606.)

## **Other Activities**

### **ME 591. Graduate Seminar**

0 credit

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.

### **ME 593. Special Topics**

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.) See the **SUPPLEMENT** section of the on-line catalog at [www.wpi.edu/+gradcat](http://www.wpi.edu/+gradcat) for descriptions of courses to be offered in this academic year.

### **ME 598. Directed Research**

For M.S. or Ph.D. students wishing to gain research experience peripheral to their thesis topic, or for doctoral students wishing to obtain research credit prior to admission to candidacy.

### **ME 599. Thesis Research**

For master's students wishing to obtain research credit toward their thesis. (Prerequisite: Consent of Thesis Advisor.)

### **ME 693. Advanced Special Topics**

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.) See the **SUPPLEMENT** section of the on-line catalog at [www.wpi.edu/+gradcat](http://www.wpi.edu/+gradcat) for descriptions of courses to be offered in this academic year.

### **ME 698. Predissertation Research**

Intended for doctoral students wishing to obtain research credit prior to admission to candidacy. (Prerequisite: Consent of Dissertation Advisor.)

### **ME 699. Dissertation Research**

Intended for doctoral students admitted to candidacy wishing to obtain research credit toward their dissertations. (Prerequisite: Consent of Dissertation Advisor.)

## Program of Study

WPI physics graduate program prepares students for careers in research that require a high degree of initiative and responsibility. Prospective employers are industrial laboratories, government or non-profit research centers, as well as colleges or universities.

WPI's physics courses are generally scheduled during the mornings but with sufficient flexibility to accommodate part-time students. Special topics courses in areas of faculty research interest are often available. To improve the course offerings and opportunities for graduate students, the Departments of Physics at WPI and Clark University share their graduate courses. Please visit the Clark University Physics Department web pages for more information on their offerings.

## Admission Requirements

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). The thesis option requires the completion and defense of a M.S. thesis as well as a seminar presentation based on the thesis research. The seminar and defense may be done in conjunction. The non-thesis option requires a satisfactory performance on the Qualifying Examination.

### 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.

One year of residency and passage of a qualifying examination are required.

A minimum of 60 credits must be earned at WPI.

The Qualifying Examination for the doctor of philosophy degree is usually administered each year at the beginning of the second semester. Ph.D. aspirants who enter after the bachelor's degree may take the examination during their first year of graduate school, and are expected to take the examination by the end of their second year. There is no penalty for failing or not taking the examination during the first year. Students who fail the examination during their second year must pass the examination when it is next offered. The Qualifying Examination will include, but is not limited to, material taken from PH 511, PH 514-515, PH 522 and PH 533. Each student's academic work is reviewed on an annual basis by the Physics Department Graduate Committee. Continuation of student status is based on satisfactory progress toward a degree, coursework, research, teaching, and service to the Department. Renewals of research and teaching assistantships are dependent on satisfactory performance of required duties.

## Research Areas

### Quantum Physics:

**Cold atoms** – Bose-Einstein Condensation of bosons and fermions, atom wave guides and interferometers.

**Quantum Information** – Bell's theorem, quantum algorithms.

**Wavefunction Engineering** – nanostructures, finite-element modeling of quantum systems and well, field theory.

### Optics:

**Photonics** – Fourier optics, photon statistics, nonlinear optics, fiber optics, coherent states and squeezed states, optical properties of rough surfaces and of thin metal films.

**Spectroscopy** – laser spectroscopy of impurity ions in glasses, quasielastic/ inelastic light scattering and excitation/ modulation spectroscopy of superlattices, thin films, surface phenomena.

**Lasers** – development of infrared fiber lasers and materials, mid-IR and FIR quantum cascade laser design.

### Condensed Matter:

**Semiconductors** – optical properties of superlattices, heterostructure laser design, spintronics in diluted magnetic semiconductors, devices.

**Magnetic Solids** – Magnetic impurities in semiconductors: diluted magnetic semiconductors and the onset of ferromagnetism in spintronic materials.

**Nanomechanics** – mechanical properties of nanostructures, atomic-force microscopy instrumentation, and interpretation.

### Soft Condensed Matter/ Complex Fluids:

**Biophysics** – hydration effects on protein dynamics, thermodynamics of proteins and DNA, self-assembly of biomaterials, dielectric relaxation spectroscopy, relation calorimetry, resonant ultrasound spectroscopy.

**Polymers** – molecular properties of small sample volumes and single molecules, polymer and bio-macromolecular solutions, surfactants, colloids.

**Liquid Crystals** – thermotropic/lyotropic/colloidal systems, phase transitions and critical phenomena, cooperative behavior and self-assembly, quenched random disorder effects, calorimetry instrumentation.

**Complex Liquids/Glasses** – theory and simulations, diffusion and transport properties, light scattering spectroscopy of liquids and polymer melts, wetting phenomena, Casimir forces.

**Glasses** – theory and simulation, thermodynamics, relaxations.

## Physics Education

Research in physics education focuses on aspects of teaching and learning physics, spanning a broad range of topics from psychology- in studying student behaviors-to computer science-in studying uses of new interactive technologies in learning.

## Faculty

**G. S. Iannacchione**, Associate Professor and Department Head; Ph.D., Kent State University; Soft condensed matter physics/complex fluids, liquid-crystals, calorimetry, and order-disorder phenomena.

**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.

**R. Garcia**, Assistant Professor; Ph.D., Penn State University; Casimir forces, phase transitions, and wetting phenomena.

**T. H. Keil**, Professor; Ph.D., University of Rochester; Solid state physics, mathematical physics, fluid mechanics.

**S. Koehler**, Assistant Professor; Ph.D., University of Chicago; Structure and dynamics of colloids and granular systems, micro-rheology of complex fluids.

**C. Koleci**, Adjunct Assistant Professor, Director of Physics; Ph.D., Brown University; Physics education.

**G. D. J. Phillies**, Professor; D.Sc., Massachusetts Institute of Technology; Light scattering spectroscopy, biochemical physics, polymers.

**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.

**I. Stroe**, Assistant Professor; Ph.D., Clark University; Experimental biophysics, protein structure, dynamic, and functionality.

**E. Tüzel**, Assistant Professor; Ph.D., University of Minnesota; Statistical mechanics and polymer physics applied to biology and materials science.

**A. Zozulya**, Professor; Ph.D., Lebedev Physics Institute; Nonlinear optics, photorefractive materials, atom pipes.

## 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 597. Special Topics**

(credits are arranged: 1-3)

See the **SUPPLEMENT** section of the on-line catalog at [www.wpi.edu/+gradcat](http://www.wpi.edu/+gradcat) for descriptions of courses to be offered in this academic year.

**PH 598. Directed Research**

(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**

(varies)

Each student will work under the supervision of a member of the department on an experimental or theoretical problem.

**PH 699. Ph.D. Dissertation**

(varies, no more than 30)

Required in the last semester or two for the writing and defending of a Ph.D. dissertation.

## Program of Study

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

The M.S. program in Robotics Engineering requires 36 credit hours of work. Students may select a non-thesis option, which requires a 6-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 (6 credits)
  - RBE 500 Foundations of Robotics
  - ME/RBE 501 Robot Dynamics
- Computer Science: 3 credit hours selected from the following courses:
  - CS 509 Design of Software Systems
  - CS 534 Artificial Intelligence
  - CS 546 Human-Computer Interaction
- Electrical and Computer Engineering: 3 credit hours selected from the following courses:
  - ECE 502 Analysis of Probabilistic Signals and Systems
  - ECE 503 Digital Signal Processing
  - ECE 504 Analysis of Deterministic Systems
- Mechanical Engineering: 3 credit hours selected from the following courses:
  - ME 523 Applied Linear Control
  - ME 527 Dynamics
  - ME 623 Applied Nonlinear Control

### 2. Engineering Context (6 credits)

- Management: 3 credit hours selected from the following courses:
  - ETR 592 New Venture Management And Entrepreneurship
  - MIS 576 Project Management
  - MKT 563 Marketing of Emerging Technologies
  - OBC 511 Interpersonal and Leadership Skills for Technological Managers
  - OIE 546 Managing Technological Innovation
- Systems Engineering: 3 credit hours selected from courses prefixed by SYS at the 500 level or above.

### 3. Capstone / Thesis (6-9 credits)

- A 6 credit hour capstone design project/practicum or a 9 credit hour thesis.

**4. Electives (6-9 credits):** Sufficient course work selected from courses at the 500 level or above with a prefix of RBE, CS, ECE, MA, ME, or SYS to total 36 credit hours. Courses at the 4000 level may also be taken as electives with the prior approval of the RBE Graduate Committee.

**5. Only one** of ECE 504 and ME 523 may count towards the Robotics M.S. Degree.

## 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 research-based thesis, students may elect a project or practicum to include a design/research component in their graduate program. For an M.S. Degree in Robotics Engineering this can be accomplished by completing a 6 credit capstone design project RBE 598 or a practicum RBE 596. The capstone design project must be approved by the Robotics Engineering Graduate Program Committee and must demonstrate significant graduate-level work involving Robotics Engineering. The capstone design project must include substantial analysis and/or design related to robotics engineering and will conclude with a substantial written report.

A practicum 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.

Students completing a capstone design project or practicum must deliver a public oral presentation to a committee consisting of the supervising faculty member and two additional WPI faculty members (in the case of a practicum, the on-site liaison and one additional WPI faculty member). Successful completion of the project or practicum will be verified by this committee.

### Transfer Credit

A student may petition for permission to use graduate courses taken at other 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 BS/MS 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.

## BS/MS in Robotics Engineering

The requirements for the proposed M.S. in Robotics Engineering are structured so that undergraduate students 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 Robotics Engineering.

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:

- Up to three graduate courses 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 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 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 three credits can be earned towards fulfillment of the capstone design requirement by double counting a senior undergraduate project if it involves substantial use of Robotics Engineering at an advanced level, subject to approval by the Robotics Engineering Graduate Program Committee. In this case, students may satisfy the capstone design requirement by completing 3 credits of capstone design project RBE 598 or practicum RBE 596, not necessarily related to the senior undergraduate project.

### Summary of Credit Requirements

	MS Thesis	MS Non-Thesis	BS/MS
Robotics Core	15	15	15
Engineering Context	6	6	6
Electives	6	9	9
Thesis	9	—	—
Capstone Design / Practicum	—	6	6
Double Count	—	—	(12)
<b>Total</b>	<b>36</b>	<b>36</b>	<b>24</b>

## Faculty

**Michael A. Gennert**, Associate Professor, Computer Science Department Head, Robotics Engineering Program Director; Sc.D., Massachusetts Institute of Technology; Image processing, image understanding, artificial intelligence, robotics, scientific databases, theoretical computer science.

**Fred J. Looft**, Professor, Electrical and Computer Engineering Department Head, Robotics Engineering Program Associate Director; Ph.D., Michigan; Instrumentation, digital and analog systems, signal processing, biomedical engineering, microprocessor systems and architectures, space-flight systems.

**Gretar Tryggvason**, Professor, Mechanical Engineering Department Head, Robotics Engineering Program Associate Director; Ph.D., Brown University; Numerical modeling of multiphase flows.

**Holly K. Ault**, Associate Professor; Ph.D., Worcester Polytechnic Institute; Geometric modeling, mechanical design, CAD, kinematics, biomechanics, rehabilitation engineering.

**David C. Brown**, Professor; Ph.D., Ohio State; Knowledge-based design systems, artificial intelligence.

**Michael J. Ciaraldi**, Professor of Practice; M.S., Rochester Institute of Technology, University of Rochester; Robotics education, software engineering, real-time and embedded systems.

**David Cyganski**, Professor; Ph.D., Worcester Polytechnic Institute; Optimization and security of Internet communications, distributed and fault-tolerant computing, CORBA, machine vision, automatic target recognition.

**Eben C. Cobb**, Visiting Assistant Professor; Ph.D., University of Connecticut; Computer aided design and kinematics, design of high-speed precision equipment, dynamics of high-speed rotating equipment, smart structures, vibration control.

**Michael A. Demetriou**, Associate Professor, 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, control of mechanical systems.

**R. James Duckworth**, Associate Professor; Ph.D., Nottingham University; Embedded computer system design, computer architecture, real-time systems, wireless instrumentation, rapid prototyping, logic synthesis.

**Alexander E. Emanuel**, Professor; D.Sc., Israel Institute of Technology; Power quality, power electronics, electromagnetic design, high-voltage technology.

**Gregory Fischer**, Assistant Professor, Ph.D., Johns Hopkins University; Medical robotics, computer assisted surgery, robot control, automation, sensors and actuators.

**Mustapha S. Fofana**, Associate Professor, Ph.D., University of Waterloo, Waterloo, Canada; Delay dynamical systems, nonlinear machine-tool chatter, stochastic nonlinear dynamics, reliability dynamics and control of medical ambulance, design and manufacturing of combat feeding systems, CNC machining dynamics and control, sustainable lean manufacturing systems.

**Cosme Furlong**, Assistant Professor; Ph.D., Worcester Polytechnic Institute; MEMS and MOEMS, nanotechnology, mechatronics, laser applications, holography, computer modeling of dynamic systems.

**Allen H. Hoffman**, Professor; Ph.D., University of Colorado; Biomechanics, biomaterials, biomedical engineering, rehabilitation engineering, biofluids, continuum mechanics.

**Ximing Huang**, Assistant Professor; Ph.D., Virginia Tech; Reconfigurable computing, VLSI integrated circuits, networked embedded systems.

**Islam I. Hussein**, Assistant Professor; Ph.D., University of Michigan; Cooperative control of intelligent multiple vehicle sensor network systems, geometric mechanics and control, optimal control theory.

**Robert W. Lindeman**, Assistant Professor; Ph.D., George Washington; Human-computer interaction, haptics, virtual environments.

**William 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.

**Robert L. Norton**, Milton Prince Higgins II Professor; M.S., Tufts University; Mechanical design and analysis, dynamic signal analysis, computer-aided engineering, computer-aided design, finite element method, vibration analysis, engineering design, biomedical engineering.

**Taskin 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.

**Gary F. Pollice**, Professor of Practice; M.S., University of Massachusetts, Lowell; Software engineering, quality and testing, programming languages, collaborative development and processes.

**Charles Rich**, Professor; Ph.D., Massachusetts Institute of Technology; Artificial intelligence and its intersections with human-computer interaction, interactive media and game development, robotics, intelligent tutoring systems, knowledge-based software tools.

**Yiming (Kevin) Rong**, John Woodman Higgins Professor and Associate Director Manufacturing & Materials Engineering; Ph.D., University of Kentucky; Manufacturing systems and processes, heat treatment process modeling and simulation, CAD/CAM, computer-aided fixture design and verification.

**Kenneth A. Stafford**, Adjunct Assistant Professor and Robotics Resource Center Director; M.S., Air Force Institute of Technology; Robotics systems design.

**James D. Van de Ven**, Assistant Professor; Ph.D., University of Minnesota; Propulsion systems, energy storage, kinematics, manipulator design, machine design.

## 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.)

### **ME/RBE 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 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. See the **SUPPLEMENT** section of the on-line catalog at [www.wpi.edu/+gradcat](http://www.wpi.edu/+gradcat) for descriptions of courses to be offered each academic year.)

### **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.)

## Program of Study

The Social Science & Policy Studies department 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.

## 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, the department of Social Science and Policy Studies at WPI has developed a program of several on-line graduate courses in system dynamics.

The Department of Social Science and Policy Studies offers a graduate certificate program to create meaningful training in System Dynamics for people who may not seek a graduate degree, or who might wish to acquire basic training in the area prior to entering a degree program. This graduate certificate can be pursued entirely on line through courses implemented by WPI's Advanced Distance Learning Network (ADLN). For information about the ADLN option, please contact Pam Shelley (pshelley@wpi.edu). The structure and requirements for the program are detailed below.

## Requirements

1. A student must work with a faculty advisor to delineate a Plan of Study comprising 15 credit hours of graduate coursework on system dynamics. To be counted towards the certificate, the plan must be developed not later than completion of his/her second course.
2. A student must complete his/her coursework in System Dynamics selected from the following curriculum.
  - a) At least 3 credit hours of coursework selected from the following courses or their equivalents:
    - SD 550 System Dynamics Foundation: Managing Complexity (3 credits)
    - SD 551 Modeling and Experimental Analysis of Complex Problems (3 credits)
    - b) 9-12 credit hours of coursework selected from the following courses:
      - SD 552 System Dynamics for Insight (3 credits)
      - SD 553 Model Analysis and Evaluation Techniques (3 credits)
      - SD 554 Real World System Dynamics (3 credits)
      - SD 555 Psychological Foundations of System Dynamics (3 credits)
      - SD 560 Strategy Dynamics (3 credits)
      - SD 561 Environmental Dynamics (3 credits)
      - SD 562 Project Dynamics (3 credits)
      - SD 565 Macroeconomic Dynamics (3 credits)
      - SD 590 Special Topics in System Dynamics (credit as specified)

## 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 SSPS department graduate program committee and approved by the department head 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 the students to understand the policy implementation 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 understanding cross-disciplinary issues, thus making him or her innovative contributors to their respective work settings. The WPI Masters Degree in System Dynamics may be pursued on-line. For more information, go to <http://www.wpi.edu/+ADLN>.

## Degree Requirements

Students must complete 30 credit hours of course work. At least 21 of these must be in system dynamics and the remaining nine must be in mathematics, organizational studies, economics, or system dynamics as applied to problem solving in a variety of domains. Up to six of these latter credit hours may be completed as supervised project work. Three of these credits can also be earned by double counting a part of the junior and senior undergraduate projects involving system dynamics, if the SS&PS Department views this work to be equivalent to a graduate course. 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. If the student has earned a Graduate Certificate in System Dynamics from WPI, the plan of study must be submitted with the application for the Masters Degree program. The plan of study must be approved by the SS&PS Department.

### 1. Required courses (6 credits)

- SD 550 System Dynamics Foundation: Managing Complexity (3 credits)
- SD 551 Modeling and Experimental Analysis of Complex Problems (3 credits)

### 2. 6 to 9 credit hours of course work selected from the following courses:

- SD 552 System Dynamics for Insight (3 credits)
- SD 553 Model Analysis and Evaluation Techniques (3 credits)
- SD 554 Real World System Dynamics (3 credits)
- SD 555 Psychological Foundations of System Dynamics (3 credits)

### 3. 9 to 12 credit hours of course work selected from the following courses:

- SD 560 Strategy Dynamics (3 credits)
- SD 561 Environmental Dynamics (3 credits)
- SD 562 Project Dynamics (3 credits)
- SD 565 Macroeconomic Dynamics (3 credits)

### 4. 3 to 9 credit hours of elective course-work selected from the following:

- SD 590 Special Topics in System Dynamics (credit as specified)
- MA 510/CS522 Numerical Methods (3 credit hours)

- MA 512 Numerical Differential Equations (3 credit hours)
- Approved graduate coursework in an application area (e.g., economics, psychology, management, engineering, or applied sciences)

A selection from the following WPI on-line courses may be taken to meet this part of the degree requirement:

- ACC 501 Financial Accounting (2 credits)
- FIN 502 Finance (2 credits)
- FIN 508 Economics of the Firm (2 credits)
- FIN 509 Domestic and Global Economic Environment of Business (2 credits)
- OBC 503 Organizational Behavior (2 credits)
- OBC 531 Managing Organizational Change (3 credits)
- CE 574 Water Resources Management (3 credits)
- CE 579 Planning & Designing for a Sustainable Built Natural Environment (3 credits)

### 5. Up to 6 credit hours of directed research

All courses selected by the student must appear in the graduate catalog and must be approved by the SS&PS Department.

## 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 SS&PS Department based on all of the factors presented in the application.

## BS/MS 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:

- 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.
- Up to four graduate courses in categories one to five 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.
- 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 SS&PS Department.
- 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 SS&PS 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, Social Science & Policy Studies, 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.

The specific course requirements for the interdisciplinary masters in system modeling include the following:

1. Nine credit hours of required System Dynamics coursework selected from among the following:
  - SD 550 System Dynamics Foundation: Managing Complexity (3 credit hours)
  - SD 551 Modeling and Experimental Analysis of Complex Problems (3 credit hours)
  - SD 552 System Dynamics for Insight (3 credit hours)
  - SD 554 Real-World System Dynamics (3 credit hours)
  - Independent graduate studies and selected topics as approved by the administering faculty (up to 3 credits)
2. Six credit hours of elective courses in System Dynamics to be selected from among the following:
  - SD 553 Advanced Techniques for System Dynamics (3 credit hours)
  - SD 555 Psychological Foundations of System Dynamics (3 credit hours)
  - SD 561 Environmental Dynamics (3 credit hours)
  - SD 562 Project Dynamics (3 credit hours)
  - SD 560 Strategy Dynamics (3 credit hours)
  - SD 565 Macroeconomic Dynamics (3 credit hours)
  - Independent graduate studies and selected topics as approved by the administering faculty (up to 3 credit hours)
3. Six credit hours of required Mathematics coursework selected out of the following:
  - MA 508 Mathematical Modeling (3 credit hours)
  - MA 510 Numerical Methods (3 credit hours)
  - MA 540 Probability and Mathematical Statistics I (3 credit hours)
4. Nine credit hours in an application area (coursework and/or research) in mathematical sciences, engineering or science, excluding social science, to be selected from among the following:
  - MA 514 Numerical Differential Equations (3 credit hours)
  - MA 541 Probability and Mathematical Statistics II (3 credit hours)

- MA 542 Regression Analysis (3 credit hours)
- Approved graduate coursework in a related application area (mathematical sciences, management, engineering or science excluding social science)
- Up to 6 credit hours of directed research

## Interdisciplinary Doctorate in Social Science

The Social Science and Policy Studies Department offers doctoral studies under the WPI interdisciplinary category described on page 78.

### Administering Faculty

Interdisciplinary doctoral programs involving SSPS have currently been formed in coordination with faculty in ME, CS, CEE, ECE, and MA departments. For administrative purposes, SSPS will serve as host department in each instance.

### Admission

Admission criteria for the doctoral program are outlined on pages 12 and 14. Applicants to the SSPS interdisciplinary doctoral program must have prior BS and MS 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. The doctoral program committee must be approved by CGSR.

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. This Plan of Study must also be approved by CGSR. Minimum and typical requirements for the Plan of Study are discussed below.

## Requirements for the Interdisciplinary Social Science Doctorate at WPI

In addition to meeting the general requirements of the doctoral degree at WPI, students in the interdisciplinary social science 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 SSPS: 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 MS 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-MS Credits: 60**

### Initial Coursework Leading to the Qualifying Exam

The student may take no more than 18 credit hours of graduate coursework prior to taking a qualifying exam. The content of these 18 credit hours must be established and agreed to by the student's doctoral program committee, and then approved by CGSR, as a part of the student's

Plan of Study. Graduate courses from other departments and universities may be included if recommended by the student's doctoral program committee.

### Credit Transfer

Up to 1/3rd of the credit requirements for the doctoral degree may be satisfied from courses taken elsewhere. All credit transfer requests must be approved by the student's doctoral program committee and CGSR, and must be shown on the student's Plan of Study.

### Qualifying Exam

In addition to the general WPI requirements for a Ph.D., students studying for the SSPS interdisciplinary doctorate must pass a qualifying examination. This examination will test the basic knowledge and understanding of the student in the disciplines covered by the research. The exam questions will be developed by the student's doctoral program committee, and may take the form of written, take-home, or oral questions at the committee's discretion. Students are allowed at most two attempts at passing the examination, and may take a maximum of 18 credits prior to passage. The schedule of the qualifying examination must be approved by CGSR.

### Post-Qualifying Exam Coursework, Research, and Candidacy Exam

Once the qualifying examination has been passed, the student continues toward preparation of a thesis proposal, and its defense in a candidacy exam. This preparation will involve at least 6 additional credits of graduate coursework, and at most 18 credit hours of dissertation research (prior to passing the candidacy exam). The student will prepare a thesis proposal and defend it in a candidacy exam. The exact format for the preparation of the proposal and its defense will be determined by the student's doctoral program committee.

### Residency

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

### Dissertation - Final Defense

Following the passing of the candidacy exam, a minimum of 12 credit hours of dissertation research, under the guidance of the doctoral program committee, is required for the preparation and defense of the doctoral dissertation. At this time, additional balance credits of graduate coursework or dissertation credits should be taken to complete the 60 required total post-M.S. credits, and to make at least 30 credits of dissertation credits. All dissertations must be defended in an oral presentation and accepted by the student's doctoral program committee. Revisions may or may not be orally defended at the discretion of the doctoral program committee, but must be approved by doctoral program committee chair.

For additional information on university requirements, see page 24.

## Faculty

**James K. Doyle**, Associate Professor and Department Head; Ph.D., University of Colorado/Boulder, 1991; judgement and decision making, mental models of dynamic systems, evaluation of system dynamics interventions

**James M. Lyneis**, Professor of Practice; 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](mailto:jmlyneis@wpi.edu)

**Oleg V. Pavlov**, Assistant Professor; Ph.D., University of Southern California, 2000; economics of information systems, political economy, system dynamics, computational economics, complex economic dynamics; [opavlov@wpi.edu](mailto:opavlov@wpi.edu).

**Michael 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](mailto:mjradz@wpi.edu)

**Khalid Saeed**, Professor; Ph.D., Massachusetts Institute of Technology, 1981; sustainable economic development, system dynamics; organizational development, political economy; [saeed@wpi.edu](mailto:saeed@wpi.edu)

## Adjunct Faculty

**Robert Eberlein**, Ph.D., Massachusetts Institute of Technology, President, Ventana Systems, Inc

**Andrew Ford**, Professor; Ph.D., Washington State University; Regional Planning

**James Hines**, Ph.D., Senior Lecturer, Massachusetts Institute of Technology

**John Morecroft**, Senior Fellow, Management Science and Operations, London Business School

**Jim Thompson**, Ph.D.

**Kim Warren**, Ph.D., Chairman, Global Strategy Dynamics

## 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 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 manag-

ers) 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 recommended 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 555. Psychological Foundations of System Dynamics Modeling

This course examines the cognitive and social processes underlying the theory and practice of system dynamics. The errors and biases in dynamic decision making that provide the primary rationale for the use of system dynamics modeling will be traced to their root causes in cognitive limitations on perception, attention, and memory. Group processes that influence the outcome of modeler-client interactions and appropriate psychological techniques for eliciting and using mental data to support model building will also be addressed. Additional topics will include the reliability of alternate data sources for modeling, techniques for quantifying soft variables, design issues in group model building, the relative advantages of qualitative and quantitative modeling, and client attitudes toward modeling. (Prerequisite: SS550 System Dynamics Foundation: Managing Complexity or permission of the instructor.)

### 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 organisations. 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. (Prerequisite: SD 550 System Dynamics Foundation: Managing Complexity or permission of the instructor.)

### **SD 561. Environmental Dynamics**

Environmental Dynamics introduces the system dynamics students to the application in environmental systems. The course materials include the book *Modeling the Environment*, a supporting website, lectures and the corresponding power point files. Students learn system dynamics with examples implemented with the Stella software. The course includes a variety of small models and case applications to watershed management, salmon restoration, and incentives for electric vehicles to reduce urban air pollution. The students conclude the course with a class project to improve one of the models from the text. The improvements may be implemented with either the Stella or the Vensim software. (Prerequisite: SD 550 System Dynamics Foundation: Managing Complexity.)

### **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. See the **SUPPLEMENT** section of the on-line catalog at [www.wpi.edu/+gradcat](http://www.wpi.edu/+gradcat) for descriptions of courses to be offered in this academic year.)

# Campus Telephone Numbers

## Main Switchboards

Main Campus  
(Worcester) ..... 508-831-5000

## Academic Departments & Programs

Air Force & Aerospace  
Studies ..... 508-831-5747  
Biology & Biotechnology... 508-831-5543  
Biomedical Engineering..... 508-831-5447  
Chemical Engineering..... 508-831-5250  
Chemistry &  
Biochemistry..... 508-831-5371  
Civil & Environmental  
Engineering..... 508-831-5294  
Computer Science..... 508-831-5357  
Electrical & Computer  
Engineering..... 508-831-5231  
Fire Protection  
Engineering..... 508-831-5593  
Humanities & Arts ..... 508-831-5246  
Interdisciplinary &  
Global Studies  
(undergraduate) ..... 508-831-5547  
Management..... 508-831-5218  
Manufacturing  
Engineering..... 508-831-5633  
Materials Process  
Engineering..... 508-831-5633  
Materials Science  
& Engineering ..... 508-831-5633  
Mathematical Sciences ..... 508-831-5241  
Mechanical Engineering..... 508-831-5236  
Metal Processing Institute .. 508-831-5992  
Military Science ..... 508-831-5268  
Physical Education  
& Athletics..... 508-831-5243  
Physics ..... 508-831-5258  
Social Science &  
Policy Studies..... 508-831-5296

## Offices & Services

Academic Advising..... 508-831-5381  
Academic Technology  
Center..... 508-831-5220  
Accounting Office..... 508-831-5203  
Administrative Services ..... 508-831-5150  
Admissions (Graduate)..... 508-831-5301  
Admissions  
(Undergraduate)..... 508-831-5286  
Advanced Distance  
Learning Network..... 508-831-6789  
Alumni Office 508-831-5600  
Bookstore  
(Barnes&Nobel@WPI) ..... 508-831-5247  
Campus Police  
(non-emergency) ..... 508-831-5433  
Campus Police  
(emergency) ..... 508-831-5555  
Career Development  
Center..... 508-831-5260  
Computing &  
Communications Center.... 508-831-5136  
Continuing &  
Professional Education ..... 508-831-5517  
Corporate and  
Foundation Relations..... 508-831-5600  
Dining Services ..... 508-831-5253  
Diversity Programs..... 508-831-5796  
Events ..... 508-831-5613  
Extended Education..... 508-831-5517  
Financial Aid..... 508-831-5469  
Graduate Admissions ..... 508-831-5301  
Graduate Studies..... 508-831-5574  
Health Services..... 508-831-5520  
Helpdesk..... 508-831-5888  
Human Resources ..... 508-831-5470  
International Students  
& Scholars ..... 508-831-6030

Library Services (George  
C. Gordon Library)..... 508-831-5410  
Mail Services ..... 508-831-5523  
Marketing &  
Communications ..... 508-831-5305  
Massachusetts Academy of  
Mathematics and Science... 508-831-5859  
Media Relations ..... 508-831-5610  
Ombuds Office ..... 508-831-5290  
Payroll..... 508-831-5877  
Plant Services ..... 508-831-5500  
President's Office..... 508-831-5200  
Projects Program ..... 508-831-5457  
Property Administration .... 508-831-5137  
Provost's Office ..... 508-831-5222  
Registrar's Office ..... 508-831-5211  
Research Administration .... 508-831-5359  
Residential Services ..... 508-831-5645  
Scheduling (academic) ..... 508-831-5457  
Secretary of the Faculty ..... 508-831-5135  
Snow Closings/Delays..... 508-831-5470  
Sports Information..... 508-831-5243  
Student Activities ..... 508-831-5291  
Student Development &  
Counseling Center..... 508-831-5540  
Student Affairs &  
Campus Life ..... 508-831-5060  
Student Night Assistance  
Patrol (SNAP) ..... 508-831-6111  
Summer Programs..... 508-831-5366  
Telecommunications ..... 508-831-5210  
University Advancement .... 508-831-5600  
Web Development ..... 508-831-5305  
Women's Programs..... 508-831-5819

# Notes

# Notes

# Index

- Academic Standards 17
- Admission 12
- Advanced Distance Learning Network (ADLN) 11
- Advanced Graduate Certificates 8
- Application Requirements 15
- Applied Mathematics 93
- Applied Statistics 93
- Audit 21
  
- Berkey, Dennis 1
- Biochemistry 48
- Biology and Biotechnology 28
- Biomedical Engineering 30
- Bookstore 24
- BS/MS Program 7
- Business, School of 35
  
- Campus Map 132
- Campus Telephone Numbers 127
- Career Development Center 24
- Certificate in College Teaching 78
- Chemical Engineering 44
- Chemistry and Biochemistry 48
- Civil and Environmental Engineering 51
- Class Cancellation 24
- Collaborative for Entrepreneurship and Innovation 38
- Colleges of Worcester Consortium 4
- Combined Bachelor/Master's Program 7
- Computer and Communications Networks 58
- Computer Resources 25
- Computer Science 60
- Conditional Admission 13
- Confirmation of Admission 13
- Construction Project Management 52
- Corporate and Professional Education 10
- Course Change Policies 21
  
- Deferred Enrollment 13
- Deferred Payment 21
- Degree Requirements 22
- Directions 131
- Dissertations 24
- Doctor of Philosophy (Ph.D.) 6
- Driving Directions 131
  
- Electrical and Computer Engineering 66
- Environmental Engineering 51
  
- Fellowships 16
- Financial Information 16
- Financial Mathematics 93
- Fire Protection Engineering 75
  
- Geotechnical Engineering 51
- Gordon Library 25
- Grading System 17
- Graduate and Advanced Graduate Certificates 8
- Graduate Calendar 2
- Graduate Certificate Program 8
- Graduate Programs by Department 5
  
- Health and Accident Insurance 21
- Highway Infrastructure 51
- Housing 26
  
- IELTS 12
- Industrial Mathematics 93
- Information Technology 36
- Insurance 21
- Interdisciplinary Master's and Doctoral Programs 7
- Interdisciplinary Programs 78
- International Graduate Student Services 26
- Internships 16
  
- Learning Sciences and Technologies (LS&T) 80
- Leave of Absence 21
- Library 25
- Locations 4
  
- Mail Services 26
- Manufacturing Engineering 84
- Marketing and Technological Innovation 36
- Master Builder 52
- Master of Business Administration 6
- Master of Engineering 6
- Master of Mathematics for Educators (M.M.E.) 6, 93
- Master of Science 6
- Materials Science and Engineering 88
- Mathematical Sciences 93
- Mechanical Engineering 103
  
- Operations Design and Leadership 36
  
- Ph.D. (Doctor of Philosophy) 6
- Physics 115
- Plan of Study 19
- Printing Services 26
- Project, Thesis, and Dissertation Advising 19
  
- Registration 20
- Research Assistantships 16
- Robotics Engineering 117
  
- School of Business 35
- Social Science & Policy Studies 121
- Structural Engineering 51
- Student ID Cards 26
- Student Loans 16
- Student Services 24
- Systems Modeling 122
- System Dynamics 121
  
- Teaching Assistantships 16
- Theses 24
- TOEFL: (Test of English as a Foreign Language) 12
- Transcripts 21
- Transfers and Waivers 13
  
- Withdrawal Policies 21
- WPI Police 24

## 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

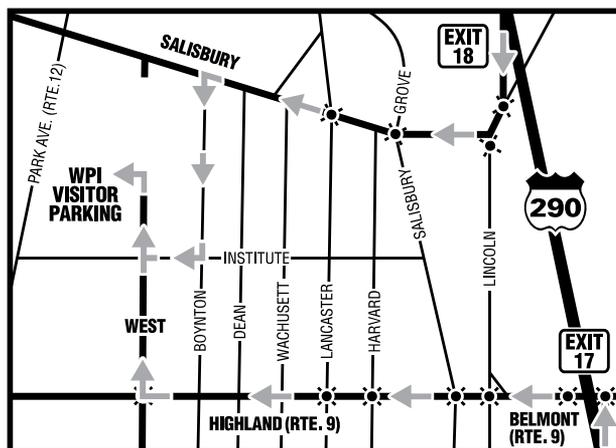
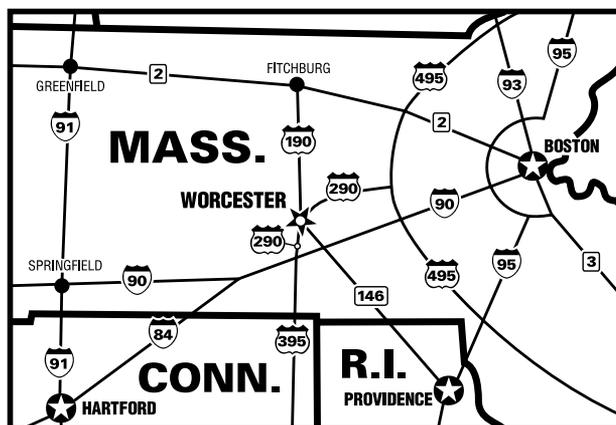
offering post-graduate instruction. In addition, undergraduate programs leading to majors in computer science, chemical, civil, electrical, industrial, manufacturing and mechanical engineering are accredited by the Engineering Accreditation Commission of the Accreditation Board for Engineering and Technology (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.

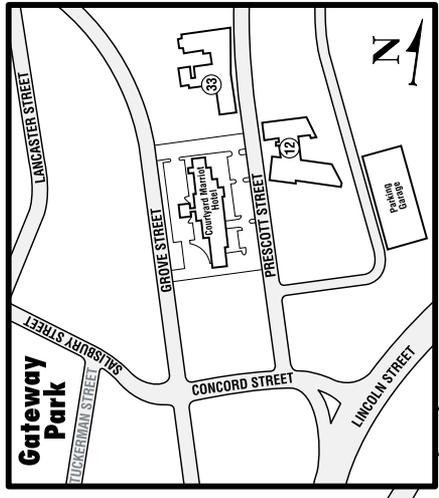
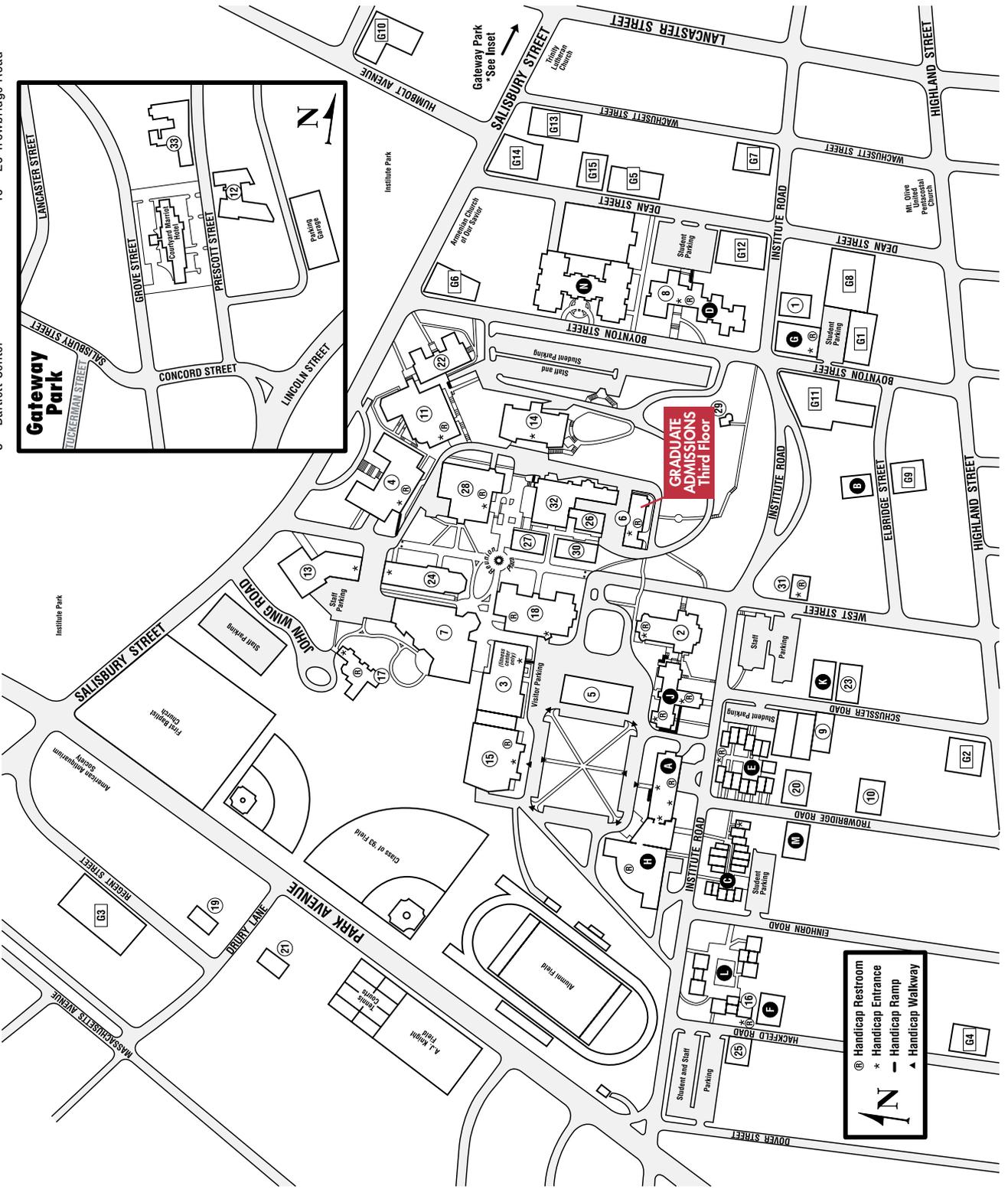




# Campus Map

- 1 Air Force and Aerospace Studies
- 2 Alden Memorial
- 3 Alumni Gym
- 4 Atwater Kent Laboratories
- 5 Bartlett Center
- 6 Boynton Hall
- 7 Campus Center
- 8 Campus Police
- 9 Collegiate Religious Ctr
- 10 20 Trowbridge Road

- 11 Fuller Laboratories
- 12 WPI Life Sciences and Bioengineering Center
- 13 Goddard Hall
- 14 Gordon Library
- 15 Harrington Auditorium
- 16 Health Center
- 17 Higgins House
- 18 Higgins Laboratories
- 19 Hughes House
- 20 International House
- 21 Jeppson House (One Drury Lane)
- 22 Kaven Hall
- 23 OASIS
- 24 Olin Hall
- 25 Plant Services
- 26 Power House
- 27 Project Center
- 28 Salisbury Laboratories
- 29 Skull Tomb
- 30 Stratton Hall
- 31 Student Development and Counseling Center
- 32 Washburn Shops and Stoddard Laboratories
- 33 85 Prescott Street



## STUDENT RESIDENCES

- A Daniels Hall
- B 16 Elbridge
- C Elsworth Apartments
- D Founders Hall
- E Fuller Apartments
- F Unity House
- G Institute Hall
- H Morgan Hall
- J Sanford Riley Hall
- K 22 Schussler
- L Stoddard Complex
- M 25 Trowbridge
- N East Hall

## GREEK HOUSES

- G1 Alpha Chi Rho
- G2 Alpha Gamma Delta
- G3 Alpha Tau Omega
- G4 Alpha Xi Delta
- G5 Lambda Chi Alpha
- G6 Phi Gamma Delta
- G7 Phi Kappa Theta
- G8 Phi Sigma Kappa
- G9 Phi Sigma Sigma
- G10 Sigma Alpha Epsilon
- G11 Sigma Phi Epsilon
- G12 Sigma Pi
- G13 Tau Kappa Epsilon
- G14 Theta Chi
- G15 Zeta Psi

Ⓠ Handicap Restroom  
 \* Handicap Entrance  
 — Handicap Ramp  
 ▲ Handicap Walkway



Enroll in graduate study at WPI:

Graduate Admissions  
Worcester Polytechnic Institute  
100 Institute Road  
Worcester, MA 01609-2280

*phone* 508-831-5301  
*fax* 508-831-5717  
*email* [grad@wpi.edu](mailto:grad@wpi.edu)  
*web* [grad.wpi.edu](http://grad.wpi.edu)