



The University of  
Science and Technology.  
And Life.™

*Graduate Studies*

# Graduate Catalog

2006 - 2007

Worcester Polytechnic Institute



## President's Message

Graduate education at WPI focuses on the highest ideals of university education: the mastery of important information and the creation of new knowledge.

A national doctoral university with a heritage of educational innovation, WPI delivered its first graduate program in 1893. Today the university offers three dozen master's and nearly 20 doctoral degree programs in engineering, science, and management, which are pursued, part-time (for practicing professionals) or full-time (for research-oriented students), on campus and via distance learning, by a diverse population of students from more than 70 nations.

Three qualities distinguish WPI's graduate programs. First, they are marked by a high degree of interdisciplinary collaboration. WPI has long been known as a place where ideas, innovations, and discovery freely cross disciplinary boundaries. Increasingly, the collaborative spirit at WPI is being expanded to include exciting academic and research partnerships with industry, government laboratories, and other universities. The university's new Life Sciences and Bioengineering Center has been expressly designed to promote research across disciplines and to facilitate external research and development partnerships.

Second, WPI graduate students benefit from their close interactions with an extraordinarily gifted and accomplished faculty. Among the ranks of WPI's tenured and tenure track faculty, 99 percent of whom hold doctoral degrees, are 17 recipients of the National Science Foundation's CAREER Award (the highest honor for young faculty), 11 winners of Fulbright scholarships, and more than 40 fellows of national and international professional societies and organizations.

Finally, WPI's graduate programs place an important emphasis on meaningful, practical applications of science and technology, a tradition that can be traced to our founding in 1865. Professionals who graduate from our part-time programs emerge with the knowledge and skills to pursue advanced careers in a range of fields – from bioinformatics to software engineering to information security to fire protection engineering.

I invite you to learn more about WPI's exceptional graduate and research programs. I am confident that you will find that they offer you the knowledge, the skills, and the experience you need to achieve your goals for advanced study, for career development, and, ultimately, for making a difference in the real world.

Sincerely,

A handwritten signature in black ink that reads "Dennis D. Berkey". The signature is written in a cursive, flowing style.

Dennis D. Berkey

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# Academic Calendar

## 2006–2007

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

### 2006

#### August 13

Teaching assistants report to campus

#### August 14

Graduate student orientation

#### August 15, 16

Teaching assistant training

#### August 31, September 1, 5

Walk-in registration for fall semester courses\*

#### August 24

First day of classes, Term A  
(*undergraduates*)

#### September 5

Fall semester graduate classes begin

#### October 12

Last day of classes, Term A  
(*undergraduates*)

#### October 24

First day of classes, Term B  
(*undergraduates*)

#### October 27

Deadline for filing application for graduation for February 2006

#### November 21–26

Thanksgiving recess

#### December 14

Term B classes end  
(*undergraduates*)

#### December 15

Fall semester ends

\*Fall Semester 2006

Projects and Registrar's Office,  
Boynton Hall:

- August 31, September 1 and 5  
8:00 a.m. - 5:00 p.m.

### 2007

#### January 11, 12, 15

Walk-in registration for spring semester courses\*\*

#### January 11

First day of classes, Term C  
(*undergraduates*)

#### January 15

Spring semester graduate classes begin

#### February 12

Deadline for filing application for graduation for May 2006

#### March 1

Last day of classes, Term C  
(*undergraduates*)

#### March 13

First day of classes, Term D

#### April 27

Spring semester graduate classes end

#### May 1

Last day of classes, Term D  
(*undergraduates*)

#### May 19

Spring 2007 commencement

#### May 11, 14 (tentative)

Walk-in Registration for summer session classes

#### May 14 (tentative)

Summer session classes begin

#### June 5

Deadline for filing application for graduation for October 2006

#### June 28 (tentative)

Last day of classes, 7-week summer courses

#### July 19 (tentative)

Last day of classes, 10-week summer courses

\*\*Spring Semester 2007

Projects and Registrar's Office,  
Boynton Hall:

- January 11, 12 and 15  
8:00 a.m. - 5:00 p.m.

## Graduate Information Sessions

#### Thursday, August 24, 2006

Campus Center, 6 p.m.

#### Thursday, September 28, 2006

Campus Center, 6 p.m.

#### Wednesday, January 10, 2007

Campus Center, 6:00 p.m.

#### Wednesday, March 14, 2007

Campus Center, 6:00 p.m.

#### Wednesday, May 9, 2007

Campus Center, 6:00 p.m.

# Graduate Calendar 2006-2007

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

# About the University and the Community

## Graduate Study at WPI

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

Opportunities for graduate study at the university include masters and doctoral graduate degree programs, graduate certificates, and advanced study for nondegree students. Off-campus study through WPI's Advanced Distance Learning Network, is also available in several academic areas. These programs bring graduate education to the workplace or home. Part-time graduate students at WPI benefit from the same faculty and academic quality as our full-time students.

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

## The University

WPI was founded in 1865 as the Worcester County Free Institute of Industrial Science, primarily through the efforts of John Boynton, a prosperous tinware manufacturer from the nearby town of Templeton, Mass. It was the merger of Boynton's vision with that of Ichabod Washburn, the community's leading industrialist, that resulted in what was then a unique educational program, one that combined scientific and technical studies with practical work in a model industrial shop.

WPI 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 close to 40 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 program 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 450 full-time and approximately 600 part-time and nondegree graduate students. They are taught by approximately 320 faculty.

## Colleges of Worcester Consortium

The Colleges of Worcester Consortium was established in 1967. In the Consortium, 20,000 students from eight four-year colleges with graduate programs, two two-year schools, a medical school and a veterinary school have access to all the educational benefits of these institutions as well as nine other specialized institutions in the area. The Consortium members and associates whose facilities and programs have been particularly useful to WPI graduate students are Assumption College, Clark University, College of the Holy Cross, Tufts School of Veterinary Medicine, 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 well known for 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 of which 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 athletic events.

In the heart of New England, the city 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.

To provide easy access to some WPI programs for working professionals, the university offers evening graduate courses in Computer Science and Electrical and Computer Engineering at its MetroWest Campus in Westborough, MA.

# Index of Graduate Programs by Department

## Biology and Biotechnology

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

## Biomedical Engineering

- Master of Science in Biomedical Engineering
- Master of Engineering in Biomedical Engineering
- Master of Engineering in Clinical Engineering
- Ph.D. in Biomedical Engineering
- WPI/UMMS Joint Ph.D. in Biomedical Engineering and Medical Physics
- Graduate Certificate

## Chemical Engineering

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

## Chemistry and Biochemistry

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

## Civil and Environmental Engineering

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

## Computer Science

- Master of Science in Computer Science
- Master of Science in Computer Science Specializing in Computer and Communications Networks (CCN)
- Ph.D. in Computer Science
- Graduate Certificate
- Advanced Certificate

## Electrical and Computer Engineering

- Master of Science in Electrical and Computer Engineering
- Master of Science in Electrical and Computer Engineering Specializing in Computer and Communications Networks (CCN)
- Ph.D. in Electrical Engineering
- Graduate Certificate
- Advanced Certificate

## Fire Protection Engineering

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

## Interdisciplinary Studies

- Master of Science, Interdisciplinary Studies
  - Impact Engineering
  - Manufacturing Engineering Management
  - Power Systems Management
  - Systems Engineering
  - Systems Modeling
- Ph.D., Interdisciplinary Studies

## Management

- 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
- Graduate Certificate

## Manufacturing Engineering

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

## Materials Process Engineering

- Master of Science in Materials Process Engineering

## Materials Science and Engineering

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

## Mathematical Sciences

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

## Mechanical Engineering

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

## Physics

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

## Social Science and Policy Studies

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

# Graduate Degrees and Programs

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 index 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.) Program

Available in the following disciplines:

- Biotechnology
- Biomedical Engineering
- Joint Ph.D. in Biomedical Engineering and Medical Physics with UMass Medical School
- Chemical Engineering
- Chemistry
- Civil Engineering
- Computer Science
- Electrical and Computer Engineering
- Fire Protection Engineering
- Interdisciplinary Studies
- Manufacturing Engineering
- Materials Science and Engineering
- Mathematical Sciences
- Mechanical Engineering
- Physics

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

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

- Applied Mathematics
- Applied Statistics
- Biochemistry
- Biology/Biotechnology\*
- Biomedical Engineering
- Bioscience Administration
- Chemical Engineering\*
- Chemistry
- Civil Engineering
- Computer Science
- 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 Engineering
  - Systems Modeling
- Marketing and Technological Innovation
- Manufacturing Engineering
- Materials Process Engineering
- Materials Science and Engineering
- Mechanical Engineering
- Operations Design and Leadership
- Physics
- System Dynamics

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

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

Offered in:

- Biomedical Engineering
- Clinical Engineering
- Environmental Engineering
- Master Builder Program

## 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 70.

## 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. This degree may be used to satisfy the Professional License requirements of Massachusetts for teachers holding the Initial License.



## **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 Department of Management at 508-831-5218, or on the web at [www.mgt.wpi.edu/Graduate/MBA/](http://www.mgt.wpi.edu/Graduate/MBA/).

## **Combined Bachelor's/Master's Program**

The Combined Bachelor's/Master's Program is a unitary program leading a student to a bachelor of science degree and to a master of business administration, master of engineering, or master of science degree. The purpose of the Combined Bachelor's/Master's Program is to give WPI undergraduates an opportunity to earn a bachelor's and a master's degree from WPI concurrently in less time than would be

required if the student were to complete work on the bachelor's degree before beginning work on the master's degree. To gain the full benefit of this program, a student should apply for the Combined Program well before the bachelor's degree is completed. *Application at the beginning of the junior year is recommended.*

For the master of science and master of engineering degrees, the Combined Program typically allows a student to complete requirements for both degrees in about one more year of full-time study than would be required to earn the bachelor's degree. With careful planning, a student can obtain a similar reduction in the amount of time required to earn an M.B.A. Undergraduate students may apply up to four courses to the master's degree (varies by department), with prior written approval from professors and the academic department. The M.S. portion of the program must be completed as a full-time student. See department descriptions for more information.

# 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/Programs/Certificates/>

## 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. For the most current listings go to <http://grad.wpi.edu/Programs/Certificates/>

## 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 (fee waived for WPI alumni) to the Graduate Studies and Enrollment Office. 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/Programs/Certificates/>. For a paper application please contact the Office of Graduate Studies and Enrollment 508-831-5301 or e-mail [gse@wpi.edu](mailto:gse@wpi.edu).

## Admission and Matriculation

Admission to a certificate program is granted by the faculty of the sponsoring department through the Graduate Studies and Enrollment 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 at <http://grad.wpi.edu/Programs/Certificates/>. 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. 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 attractive 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 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.wpi.edu/Academics/Exended/](http://www.wpi.edu/Academics/Exended/) to learn more about a customized education solution for your company and industry.

- Bioscience Regulations Management
- Power Systems Management
- Analog Electronics
- Mechanical Engineering
- Systems Engineering
- Manufacturing Engineering Management
- Information & Data Security

## Leadership Institute

The Leadership Institute at WPI is a highly customized executive education program designed to develop the management skills and leadership behaviors that are essential to a company's growth and prosperity. Designed for high-potential employees, this program can be comprised of up to five full-day sessions focusing on various aspects of leadership covering both the internal and external environment. Each day combines rich experiences with instructor-led discussions and workshops, all focused around the company's core values and mission. Full meals and accommodations are provided to keep all participants focused and involved, allowing them to build lasting relationships while achieving a higher level of personal development.

## 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. Additionally, we also offer customized training to meet an organization's specific training needs.

# Advanced Distance Learning Network (ADLN)

## Distance Learning Program

In 1979, WPI's commitment to active, lifelong learning prompted the creation of the ADLN, a partnership between several academic departments and WPI's Academic Technology Center. ADLN programs enable working professionals to continue to grow within their chosen field without having to attend any classes at the WPI campus. Persons electing to take courses via ADLN with the intention of completing a degree or certificate apply for admission to WPI utilizing the same processes and services as campus based students. Once admitted to WPI, students may take any ADLN course that is appropriate to their WPI program. All students can take ADLN courses and, within a given program's requirements, can combine on campus and ADLN classes.

## Delivery Media

Through ADLN, WPI delivers the same courses, content and material that you would receive on campus. Faculty, working with an instructional design team, determine the best technologies to use in the delivery of their distance courses. This approach to distance learning ensures that courses are kept current and the latest technologies are used. An e-mail account, access to the World Wide Web and the minimal technical requirements found at <http://www.wpi.edu/+ADLN> are required for participation in an ADLN course.

## Programs of Study

By taking courses through the Advanced Distance Learning Network, students can complete a master of business administration (M.B.A), a master of science (M.S.) in environmental engineering, fire protection engineering, or system dynamics. In addition, students may elect to take courses via ADLN to earn a graduate or advanced certificate in these disciplines.

## Credit Options

The M.B.A. program allows up to 18 foundation-level credits to be waived for those with appropriate academic backgrounds, either via straight waivers for those with appropriate coursework completed within the past six years with a grade of B or better, or via waiver exams. The M.B.A. and M.S. programs, allow students to transfer up to 9 credits from graduate-level coursework at other schools. Graduate and advanced certificate programs require all credits to come from WPI.

## Special Programs

ADLN and appropriate academic personnel are always willing to consider the addition of new programs when there is sufficient interest.

## Student Services

Academic advisors are assigned upon admission. Library services are online, and reference services are available by telephone and e-mail. All students establish a WPI UNIX account for online course access and e-mail. Technical help desk is available by e-mail or phone. Career placement and counseling are available for matriculated students. Books may be ordered toll-free from the WPI bookstore (888-WPI-BOOKS) and are typically delivered one to three days after ordering. Books may be ordered toll-free from the WPI Bookstore (888-WPI-Books) or from the web ([www.bkstore.com](http://www.bkstore.com)) and are typically delivered one to four days after ordering.

## Faculty

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

## Tuition and Fees

Tuition is \$997 per semester hour for all programs in the 2006 - 2007 academic year. This is 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. See page 17 for audit information.

## Financial Aid

Loan-based aid is available only through special arrangements. Students must be registered on a half-time basis (two courses per semester) or greater for federal loan programs. See page 17 for loan information. Other loans for 3-credit courses may be 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.

508-831-5220 (voice)  
508-831-5881 (fax)

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

<http://www.wpi.edu/+ADLN>

# Admission Information

## Applying to WPI

Applications for WPI's graduate science and engineering programs may be requested from the Graduate Studies & Enrollment Office at 508-831-5301 or online at [www.grad.wpi.edu](http://www.grad.wpi.edu).

Graduate management applications should be requested directly from the Management Department at 508-831-5218 or at <http://www.mgt.wpi.edu/graduate>.

Requirements for admission include submission of the following:

- Completed Application for Admission to Graduate Study. Applicants are strongly encouraged to complete the online application which is available at [www.grad.wpi.edu/Admissions/application.html](http://www.grad.wpi.edu/Admissions/application.html)
- Nonrefundable \$70 application fee (waived for WPI alumni and current WPI undergraduates)
- Official college transcripts from all accredited degree-granting institutions attended
- Three letters of recommendation (and/or other references) from individuals who can comment on the qualifications relevant to the applicant's admission
- Proof of English language proficiency must be submitted by all applicants for whom English is not the first language with the exception of applicants who have attended a United States college or university full time for at least one year. 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

*Note: Higher scores are required for Teaching Assistants.*

WPI's institutional code for the TOEFL is 3969. Scores are valid for two years from the test date. For more information or to register to take the TOEFL go to: [www.toefl.org](http://www.toefl.org). For more information or to registered to take the IELTS, go to: [www.ielts.org](http://www.ielts.org).

- Statement of purpose is required for individuals applying to several programs (see chart on page 14). This is a brief essay discussing background, interests, academic intent and the reasons the applicant feels he/she would benefit from the program.
- For GRE (Graduate Record Examination) and GMAT (Graduate Management Admissions Test) requirements, see the chart on page 14. WPI's school code for the GRE is 3969.
- Goddard Fellowship applicants are required to submit GRE or GMAT scores.

Incomplete applications are retained in the Graduate Studies & Enrollment Office for one year. All applications and support material become the property of WPI.

On-line applicants may check the status of their applications via the web at [http://cosmo.admin.wpi.edu/pls/prod/bwskalog.P\\_DisplLoginNon](http://cosmo.admin.wpi.edu/pls/prod/bwskalog.P_DisplLoginNon). Applicants who have submitted a paper application form may contact the Graduate Studies and Enrollment Office by e-mail ([grad\\_studies@wpi.edu](mailto:grad_studies@wpi.edu)) or by phone 508-831-5301.

WPI master's degree students seeking to continue for a Ph.D. must complete the formal application process and be admitted to the Ph.D. degree granting program.

## Deadlines

Research and teaching assistantships are typically awarded by April 1 for the fall semester. For prospective students requesting such financial assistance, completed applications must be on file no later than January 15 of the academic year preceding admission. Some programs also offer assistantships beginning in January, with an October 15 application deadline. Applicants who do not seek financial assistance may apply at any time.

## Admission

Admission to the graduate program of any department is granted by that department via the Graduate Studies & Enrollment Office. Admission to graduate interdisciplinary programs is granted by the Committee on Graduate Studies and Research.

Admission to a program generally entitles a student to work toward a degree offered by the admitting program. A student who has not been admitted to a program may not earn a degree from WPI.

Some programs, in admitting a student, determine the degree toward which the student may work. In such a case, an admitted student who wishes to work toward a different degree in the same program should consult the department head of the admitting program as to procedures to be followed and requirements. Typically, such cases involve students who have been admitted to a program leading to a master's degree and who wish to continue toward a doctorate.

An admitted student who wishes to work toward a second degree offered by a different department or program must apply to that second program for admission. Standard application procedures are followed except that no application fee is required for a second degree.

Under some circumstances a student not yet admitted to a program may earn graduate credit toward the requirements for a graduate degree. The fact that a student has been allowed to register for courses and earn graduate credit from a program does not guarantee that the student, at a later date, will be admitted to that program. Students are therefore encouraged to apply for admission to a program at the earliest possible date.

The procedure for applying as a part-time degree-seeking student is the same as that for a full-time student.

## Probational Admission

If an applicant's undergraduate record is below the usual standards for admission, but there are mitigating circumstances, probational admission may be granted. Such admission usually means that the student's performance will be reviewed at a specified time and a decision will be made about continuation in the graduate program.

## Conditional Admission

Under some circumstances (usually where the background of the student is considered to be incomplete by the department or program), conditional admission may be granted. Conditional admission indicates that the student will receive regular admission status only after overcoming the specific deficiencies as outlined in the conditional admission letter. The conditionally admitted student will be instructed as to specific course deficiencies, required minimum grades expected to be attained in these classes, time over which deficiencies are to be completed, etc. Progress of the conditionally admitted student will be monitored by the student's department. Please consult departmental descriptions for more details.

## Deferred Enrollment

An admitted student who wishes to defer enrollment must make such a request in writing to the Graduate Studies & Enrollment Office, which will seek counsel from the department involved and reply to the student.

## Transfers and Waivers

A student may petition for permission to use graduate courses taken 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. Petitions are subject to approval by the student's academic department or program, and are then filed with the Registrar. To ensure that work constitutes current practice in the field, the program may set a latest date at which each course may be applied toward the degree. Such courses are recorded on the student's WPI transcript with the grade CR, and are not included in calculations of grade point averages. However, grades earned in Biomedical Consortium courses are recorded on the transcript as if the courses were taken on campus.

Applicants may file transfer or waiver petitions with their application for admission. Notice of the approval may be included in the letter of admission to the student. This inclusion is known as admission with advanced standing.

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 9 prior credits toward satisfying requirements for the subsequent degree.

A student who withdraws from a graduate program and is later readmitted may apply course and other credits taken before 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 how many 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.
- Up to 9 credit hours from a previous master's degree 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/programs may limit the use of credit in any of these areas depending upon their specific departmental requirements.

## 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 70).

## Admission of Students Who Have Not Completed Their Baccalaureate Degrees

In general, students must have earned a bachelor's degree to be admitted, but WPI undergraduate students may apply for the Combined Bachelor's/ Master's Program. See page 7.

## Advanced Study for Nondegree Students

For individuals with an earned bachelors degree who do not want to commit themselves to a certificate or degree program but who wish to enroll in a single course or a limited number of courses in a specialized field, WPI provides the opportunity to participate in graduate level courses on an ad hoc basis. When registering for courses as a nondegree student, grading may be either conventional (A,B,C) or Pass/Fail. Pass/Fail grading must be elected at the time of registration, and courses taken on the Pass/ Fail basis are not transferable to any master's degree program.

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 graduate program at a later date. Students are therefore encouraged to apply for admission to a certificate program prior to any course registration. The maximum number of courses that may be taken as a nondegree student is four. Individual departments may establish stricter requirements.

Non-admitted students may take a maximum of four graduate courses and receive letter grades in most departments; exceptions are: three-course maximum for biomedical engineering, and electrical and computer engineering; two-course maximum for computer science and management. Once these maximums are reached, additional course registrations will be changed to pass/fail and may not be used for degree credit.

# Application Requirements

## Certificate Applications

Applicants to all graduate certificate and advanced certificate programs are required to submit to the Graduate Studies and Enrollment 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	<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	<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*
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*
Clinical 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*
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>Recommended</b> for all others	<b>Requested</b> for those without work experience	<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 70</b>			
Management	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
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>Recommended</b>	<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*

\* Waived for applicants who have attended a U.S. (English-speaking) institution full time for at least one year.

\*\* May be waived by the department graduate coordinator after a telephone interview for applicants who have earned their B.S. or M.S. 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 & Enrollment 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 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 page 2). 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, assisting in the development of theoretical advances related to faculty research projects, and conducting literature reviews on topics of research interest. 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 that must be balanced with the coursework required for the desired degree.

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. Funds may also be available to support summer research activities for students through university or departmental sources, or sponsored research projects. Some provisions exist under which WPI will pay the tuition for a student's graduate program, but provide no support beyond tuition.

## 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 Goddard and Institute fellowship awards. Fellowship awards are administered through the Graduate Studies and Enrollment Office.

Student applications and criteria for eligibility are available in the Graduate Studies & Enrollment Office and on the Web at [www.grad.wpi.edu](http://www.grad.wpi.edu). Completed fellowship applications are due in the Graduate

Studies & Enrollment Office no later than January 15 for the class beginning the following fall. Recipients receive a monthly stipend typically for 9 or 12 months and tuition for one year as a full-time student. Packages may vary. Check the website for up-to-date information.

WPI offers the following fellowships:

### GAANN

Graduate Assistants in Areas of National Need or GAANNs are provided through government grants to specific departments and research faculty. WPI has been awarded several of these grants, which are available to qualified graduate students.

### GEM Fellowships

WPI is proud to be a GEM qualified university. GEM fellowships are awarded to minorities interested in studying science and engineering at the graduate level. For more information, please contact the Graduate Studies & Enrollment Office at 508-831-5301 or [grad\\_studies@wpi.edu](mailto:grad_studies@wpi.edu).

### Goddard Fellowships

The Robert H. Goddard Fellowships are typically awarded to new full-time Ph.D. students. These highly sought-after awards span the entire research interests of the university. The Robert H. Goddard Fellowships are limited to U.S. citizens and provide the recipients with a 12-month stipend and tuition support. Support required by the student beyond the initial 12 months may be provided by the department in which the student is enrolled or by a research award from the thesis advisor. Applicants are evaluated on merit by the Faculty Selection Committee, appointed by the Provost.

### Axel F. Backlin Tuition Scholarship

Department heads may request funding from the Backlin Scholarship on behalf of deserving graduate students by contacting the Graduate Studies and Enrollment Office.

### **Marietta Anderson Fellowship**

This fellowship is awarded to an outstanding woman graduate student in her first year of doctoral studies.

### **Fire Protection Engineering Distinguished Scholars Fund**

Part of the purpose of this fund is to provide teaching assistantships to students in WPI's graduate Fire Protection Engineering Program.

### **Robert and Esther Goddard Fellowship Fund**

This fund is used to underwrite the Robert H. Goddard Fellowship, available to full-time graduate students on a competitive basis.

### **Institute Fellowships**

The Institute Fellowships are typically awarded to new, full-time PhD students. The Institute Fellowships provide recipients with a 12-month stipend and tuition support. Candidates for Institute Fellowships are nominated by their academic department.

### **The Norton Graduate Fellowship**

This fellowship is typically awarded to a first-year graduate student in manufacturing engineering.

### **Robert S. Parks Graduate Fellowship**

Established through an endowment, this fellowship shows preference to students in electrical engineering.

### **Harold Leshner Pierson Memorial Fellowship**

This fund is used to support a graduate student whose research is in an area related to medicine that is likely to result in near-term benefits to mankind.

### **Ralph E. Spaulding Fellowship**

Preference in the awarding of this graduate fellowship is given to students in civil engineering.

### **Helen E. Stoddard Fellowship in Materials Science and Engineering**

This fellowship is awarded annually to an outstanding first-year graduate student in the field of materials science and engineering.

### **Carl and Inez Weidenmiller Fellowship**

This fellowship was created from a bequest through the Carl and Inez Weidenmiller Fund.

## **Internships**

Graduate internship programs are offered in several departments. 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. For international students, if not a mandatory part of the degree program, credit must be awarded. Where credit is involved, academic advisors will assign grades and may require written reports detailing the internship's accomplishments. Students pursuing internships at not-for-profits and government agencies typically pay tuition themselves.

Two options are available for scheduling students' work and study activities: parallel and alternating formats. Under the parallel format, students work full-time during the summer. The alternating option permits cycles of full-time work and full-time study. Departments may allow students to take a course or courses during the full-time work cycle. Consult department descriptions for more information.

The work assignment is determined by the company or organization that owns the work product with the approval of the faculty advisor. The company or organization owns the work product of students on internships. Students must use care in signing agreements to ensure they do not limit their rights beyond the duration of the internships. It would be reasonable, however, that the student agrees to hold confidential material so designated for a reasonable time beyond the internship. WPI's Intellectual Property Office will provide guidance to students contemplating internships regarding such agreements.

Typically, corporate-sponsored internships are paid. Where credit is included, the corporation typically pays the tuition. Payment for internships must be at a rate comparable to full-time employment in that field at that educational level. Payment is typically made directly by the company to the student intern as an employee. With prior approval of the Provost, arrangements may be made for the company to pay WPI and WPI direct pay the student. Payments for internships sponsored by not-for-profits and government organizations may be waived.

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 stay. 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 in F-1 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, co-op education does not have to be for credit if it is based on a cooperative agreement between WPI and the employer and approved by the Career Development Center.
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 student loans. To qualify, students must be enrolled in a degree-granting program or certificate on at least a half-time basis and must be U.S. citizens or permanent residents of the United States. Available loans include the Federal Subsidized Stafford Loan, the Federal Unsubsidized Stafford Loan, and private education loans.

For information on loan programs and copies of the forms, contact WPI's Financial Aid Office at 508-831-5469, or at [www.wpi.edu/Admin/FA/](http://www.wpi.edu/Admin/FA/).

### Subsidized Federal Stafford Loan

A low-interest government subsidized loan. Students can borrow up to \$8,500 per year with repayment starting six months after graduation. Eligibility requirements: students must qualify for the loan by filing a Free Application for Federal Student Aid (FAFSA) form and demonstrating financial need. WPI also requires students to complete an institutional Graduate Personal Data Form. Students must be enrolled on at least a half-time basis (minimum of 6 credits) and must not be in default on any other educational loans.

### Unsubsidized Federal Stafford Loan

A low-interest loan not subsidized by the federal government. Borrowers are responsible for the interest while enrolled. Graduate students can borrow up to \$10,000 or cost, whichever is less. These loans carry the same interest rate as the Subsidized Stafford Loan above. Eligibility require-

ments: students must first apply for the Subsidized Stafford Loan and must not be in default on any other educational loans.

### Private Student Loans

Several private student loans are available to cover tuition and living expenses if applicable. All loans are credit-based, and students can borrow a maximum of the cost of the program less any other assistance. Since students must pass a credit review to be eligible, a co-borrower may be required. International students are eligible to borrow but a credit-worthy co-borrower who is a U.S. citizen or a permanent resident of the United States is required. Please contact the Office of Financial Aid for terms and conditions of each program available.

## Tuition and Fees

### Tuition Rate

Tuition for all courses taken by graduate students is based on a \$997 fee per credit hour for the 2006-2007 academic year.

### Audit Rate

A 50% reduced tuition rate per semester hour for the 2006-2007 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. (If MasterCard/Discover accounts are declined, either a penalty

fee will be charged or registration will be invalidated. Transcripts may also be held.) Tuition charges do not include the cost of textbooks.

### Late Registration

A \$50.00 late registration fee will be charged starting September 12, 2006 (fall semester) and January 22, 2007 (spring 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.

### Deposit

The letter of admission from the Graduate Studies & Enrollment Office indicates the semester for which admission is granted and requires that the student respond by a specified date. If accepting an offer for full-time graduate study, the student must submit a \$185 nonrefundable deposit.

### 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 may be obtained through a separate policy. Please contact the Accounting Office (508-831-5741) for further information.

# 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. Academic achievement 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 completion of 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 ap-

peal 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.

## Advising/Plan of Study

Each admitted student is assigned an academic advisor. Advisors assist students in developing a Program of Study which will meet departmental requirements and at the same time provide the opportunity to explore areas of interest to the individual.

An Advisor of Record for M.S. thesis or Ph.D. dissertation research must:

- be a tenured/tenure-track WPI faculty member and hold a dual or collaborative appointment in the degree-granting department,
- or**
- be a Professor of Practice with an appointment in the degree-granting department.

In some cases, the Advisor of Record and the Thesis Advisor will be different people. In these cases, a Thesis Advisor or Dissertation Advisor not from the department granting the graduate degree must be approved by a majority of the full-time tenured and tenure-track department faculty.

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.

Three years after the initial filing of the Plan of Study and in three-year intervals thereafter, a revised Plan of Study must be filed with the Registrar's Office prior to registration for additional academic credit. The Plan of Study must reflect all current courses that will be applicable towards the student's degree. Courses that are no longer current must be removed from the plan. The department will determine which courses are current.

# 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 (see Tuition and Fees, page 17). 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 the master's degree nor admission to graduate study. 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
- Nondegree Seeking
- Graduate Certificate or Advanced Graduate Certificate
- Student on Graduate Exchange or Internship

## 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 3 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.

## 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) or 1 credit of thesis research (for a student seeking a master's degree) establishes the student's full-time status. For the purposes of this rule, the semesters are fall (extending from August 15 through December 31), spring (extending from January 1 through May 14) and summer (extending from May 15 through August 14).

Part-time status applies to students who register for 2 to 8 credits per semester.

## Walk-In Registration Dates

### Fall Semester 2006

Projects and Registrar's Office,  
Boynton Hall:

- August 31, September 1 and 5  
8:00 a.m. - 5:00 p.m.

### Spring Semester 2007

Projects and Registrar's Office,  
Boynton Hall:

- January 11, 12 and 15  
8:00 a.m. - 5:00 p.m.

### Summer Semester 2007

The Summer Session schedule will be available on the web in December, 2006. 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.

### Withdrawal Policies

Because the university makes a financial commitment at the time a course is scheduled for instruction, **a refund of tuition and fees paid by the student\*** will be made only on the following basis:

- If notice is received after the first class, but before the second class, paid tuition and fees minus \$100 will be refunded\*.
- If notice is received after the second class, but before the third class, paid tuition and fees minus \$200 will be refunded\*.
- If notice is received after the third class, but before the fourth class, paid tuition and fees minus \$300 will be refunded\*.
- If notice is received after the fourth class, no tuition or fees will be refunded.

*\*Please note: If the tuition was paid with either Federal or Private educational loans, the refund will be in the form of the loans being cancelled. You will still owe the fee associated with your withdrawal.*

A grade of W will be recorded if written notification of withdrawal from the course is received after the third meeting of the class and not later than the following dates:

**Fall Semester:** November 10, 2006

**Spring Semester:** March 23, 2007

Withdrawal after these dates is permitted only by petition 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.

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.

# 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 CGSR, which

determines if the student has satisfied the letter and intent of the requirements for advanced degrees.

The CGSR makes its 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 24). After final approval for format of the dissertation, the Provost will notify the Registrar that the dissertation has been approved.

Once a student has satisfied the departmental candidacy requirements, the student will be permitted to enroll for

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.



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 the WPI Graduate Studies and Enrollment Office, 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.

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.

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 department decides which courses may be

used in this way. Faculty members teaching these advanced undergraduate courses may impose special requirements, appropriate to an undergraduate course being used for graduate credit, on Combined Program students.

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.

The Combined Program is a full-time program of study on both the bachelor and master's level. Full-time study means a minimum registration of 9 credit hours per semester. Once admitted to the Combined Program, a student must register every fall and spring semester until the graduate degree is completed. A student in the Combined Program who, during the fall or spring semester, has no registered activities is automatically terminated from the Combined Program, and may only be readmitted to the Combined Program by the Committee for Graduate Studies and Research via petition showing extenuating circumstances. Termination from the Combined Program does not affect a student's ability to continue toward the bachelor's degree.

Students are encouraged to apply for admission to combined degree status in their sophomore or junior year of WPI undergraduate study.

# 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 copy-

right, 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).

### Campus 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 safety 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. 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 Campus Police Office, 35 Dean Street. Campus 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, as well as x-terminals and several 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 181,000 books, plus an e-book collection of close to 30,000. The collection includes subscriptions to 900+ hard copy journals and approximately 25,000+ 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 the Tech Suite that offers plasma screen and dedicated computer, DVD and VCR player, and network access.

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.

## 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 155 undergraduates and 197 graduate students from 63 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.

- Service window open (Monday through Friday) 8 a.m. to 4:30 p.m.
- 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 in Daniels Hall, first floor, and the hours are: Monday through Friday 8 a.m. to 5 p.m. For information, call 508-831-5150.

## Student Life

The Student Life 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

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## Programs of Study

The department offers a master of science (M.S.) degree in biology and biotechnology and a doctor of philosophy (Ph.D.) degree in biotechnology. These full-time degree programs require students to successfully complete a set of required “core” 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 study research problems or questions. Graduates will have a broad knowledge of the field of biology and biotechnology as well as demonstrate detailed knowledge and applied research skills in their area of specialization. Students who complete these programs will be well prepared for further graduate education, or for employment in academics or industry.

Faculty in the Biology and Biotechnology Department have research interests in three main areas; molecular/cellular/developmental biology, molecular ecology and evolution, and applied microbial systems. Students seeking a graduate degree in biology and biotechnology engage in directed study with one of the department’s faculty in his or her research specialty area. The department suggests 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.

## 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) three of the four departmental core courses (BB575, BB576, BB577 or BB578) and the graduate seminar (BB501, 1 credit in every semester

registered for full-time study). Students must assemble an Advisory Committee of three faculty members. A minimum of two of the committee members 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) is required of all Ph.D. students. It is the intention of the faculty that the student develop for this degree a thematic focus for a minor, interdisciplinary area of study outside of the biology and biotechnology department, such that the following credit distribution be required for coursework:

#### 15 credit minimum

BB courses at the 4000 or 500 level (an M.S. in a biological field may be considered acceptable)

#### 15 credit minimum

Within the minor area of study and taken at the 4000 or 500 level (M.S. in an appropriate minor field of study may be considered acceptable)

#### 15 credit maximum

At the 4000 level or below for all requirements

#### 2 credit minimum

To meet the cultural studies requirement

#### 2 credit minimum

To meet the teaching skills requirement

Biology Seminar (BB 501) is required every semester.

Students must successfully complete (grade of B or higher) three of the four departmental core courses (BB575, BB576, BB577, or BB 578).

#### Teaching Requirement

##### 2 credit minimum

The objective of this requirement is formal training in pedagogy. It can be fulfilled by enrolling in: (1) an advanced undergraduate or graduate course in education; or (2) a mentored teaching experience (IS/P) ar-

ranged with an individual faculty member, within the major discipline of the student and the professor. This mentored teaching experience is distinguished from a teaching assistantship in that it requires significant mentored student involvement in course development, delivery and evaluation.

#### Cultural Studies Requirement

##### 2 credit minimum

Graduates of the biotechnology program will need more than technical skills to make their way in the global market. Such skills might include bioethics, and linguistic and interpretive skills that encourage a reasoned awareness and acceptance of human differences. Students may choose from offerings in bioethics, history and language to develop a focused strength in one area. Graduate work in Cultural Studies is a minimum of 2 credit hours done under the guidance of a humanities advisor. For example, a student could register for Bioethics for 2 credits.

#### 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.

#### Exams, Reports and Dissertation Defense

A Ph.D. qualifying exam is required and should be taken following the first 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 will meet each semester to review and assess the student’s progress. Candidates for the Ph.D. degree must also 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. Operational details of the program, including the student qualifying exam and dissertation defense, can be found in the graduate handbook provided to all entering students.

## 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.

**J. Bagshaw**, Professor; Ph.D., University of Tennessee; recombinant DNA mechanisms and technology, regulation of gene expression.

**R. Cheetham**, Professor; Ph.D., Purdue University; plant metabolism, physiology and ecology, environmental biology.

**T. C. Crusberg**, Associate Professor, Ph.D., Clark University; heavy metal bioremediation of industrial wastewaters, cryptobiotic desert soil crusts as indicators of environmental change in the American southwest.

**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

**J. B. Duffy**, Associate Professor; Ph.D., University of Texas; molecular signal transduction mechanisms (EGFR, TGF- $\beta$  Pathways) using drosophila model system.

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

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

**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**, Assistant Professor; Ph.D., Penn State University Medical School; gene expression, rDNA recombination and regulation mechanisms in *S. cerevisiae*

**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; PhD Genetics, Harvard University; nervous system development using *C. elegans* as a genetic model, bioinformatics approaches to understanding gene expression, computer simulations of development.

**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 502. Techniques in Electron Microscopy

This course presents the theory of operation, applications and use of scanning and transmission electron microscopy in biology. Recent original articles from the biological literature illustrate the applications of these techniques to research. Students prepare specimens for both kinds of electron microscopes and employ the standard preparative techniques including fixation, dehydration, staining, critical point drying, vacuum evaporation, embedding and sectioning. Associated photographic methods are also introduced.

### BB 505. Fermentation Biology

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

### BB 544. Bioinformatics

This course will focus on the field of bioinformatics. After providing an overview of biological data such as DNA and protein sequences and genetic markers, and providing a summary of population genetics concepts, the course will cover various methods of computational genetic analysis. Students will learn about DNA and protein sequence analysis, gene mapping, evolutionary analysis, molecular biology databases, analysis of expression data and microarray analysis.

### 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 biotech-

nology industry for the purification of products, proteins in particular, from fermentation processes. Focus is on methods which 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 as well as 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. Content and format varies to suit the interest and needs of the faculty and students. This course may be repeated for different topics covered.

### 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 three master's degree options in biomedical engineering: the Master of Science (M.S.) in Biomedical Engineering, the Master of Engineering (M.E.) in Clinical Engineering and the Master of Engineering (M.E.) in Biomedical Engineering. While the expected levels of student academic performance are the same for all 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.

The master of engineering in clinical engineering program is for those individuals interested in employment in hospitals or other clinical environments. This sub-specialty involves a close interaction with patients and the health care delivery system. An internship experience is required of all students in the clinical engineering program.

### Doctoral Programs

There are two doctor of philosophy degree options in biomedical engineering: the Ph.D. in Biomedical Engineering at WPI and the Ph.D. in Biomedical Engineering and Medical Physics offered jointly by WPI and the University of Massachusetts Medical School. In both programs, the degree of doctor of philosophy 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.

The joint WPI/UMMS Ph.D. program employs the advanced technical knowledge and expertise of engineering and medical faculty to provide students with the knowledge and skills necessary to apply engineering and scientific principles to medically related problems. A unique aspect of this program is that it utilizes the expertise and resources available from engineering- and medical-school institutions of higher education in a synergistic manner to train students in the application of engineering to medical research. The Ph.D. degree in this program is awarded jointly by WPI and UMMS, with the appropriate designation on the diploma.

### 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 motivation, the Combined Program typically allows a student to complete requirements for both degrees with only one additional year of full-time study (five years total). However, because a student must still satisfy all graduate degree requirements, the actual time spent in the program may be longer than five years. There are two degree options for students in the Combined Program: a thesis-based master of science (B.S./M.S.) option and a non-thesis master of engineering (B.S./M.E.) option. The Combined B.S./Master's Degree Program in BME adheres to WPI's general requirements for the Master of Science and Master of 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. For the joint Ph.D. program, students are also expected to have had one semester of organic chemistry, a full year of biology, and mathematics through differential equations. 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. An internship experience is required for students earning the M.E. in Clinical Engineering (3 credits). 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.

## Internships

For students in the clinical engineering program, a rotating internship is offered during the year in association with University of Massachusetts Medical Center (UMMC) and University of Massachusetts Medical School (UMMS). It includes an orientation period to acquaint the student with general hospital organization and procedures, gives a brief exposure to most of the areas listed below, and is normally required prior to specialized internships.

The specialized internship involves the student full time for approximately one month in ongoing clinical, research or engineering activities, with supervision by WPI faculty and the internship center

staff. To assure maximum student involvement and supervision, the number of positions at each of the following internship locations is limited.

1. Biomedical Engineering UMMC-Memorial Campus and UMMS
2. Cardiovascular Medicine UMMS Surgery, UMMS

The master of engineering program is considered to be a terminal professional degree.

## 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

## Noninvasive Biomedical Sensors

*Prof. Peura*

The development and testing of various invasive and noninvasive biosensors and associated bioinstrumentation. Noninvasive optical sensors for measuring glucose in diabetic individuals, urea in hemodialysis dialysate, other biochemical analytes, as well as reagentless chemistry measurements are being developed.

## 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 (19F) 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.

## Bacterial Adhesion to Biomaterials

*Prof. Camesano*

The mechanisms governing bacterial adhesion to teeth, contact lenses, and implanted or transdermal 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. Research in the laboratory is aimed at characterizing the fundamentals of microbial interaction forces, cell-to-cell interactions and microbial adhesion to biomaterials. Atomic force microscopy and related techniques are being used to probe microbe-surface or cell-to-cell interactions, in order to eventually design materials that are resistant to microbial colonization.

## Biomechanics

*Profs. Hoffman, Savilonis*

Research involving the relationship between the applied stress and the response of neurons located in soft tissues is being conducted at the University of Massachusetts Medical School. Collaborative orthopedic research on large and small animals is being conducted at Tufts University School of Veterinary Medicine. Current on-campus studies include the measurement and analysis of kinetics and kinematics of human and animal motion, and improving the mechanical design of minimally invasive medical instruments. Also, flow patterns related to arterial stenosis and the influence of arteriosclerosis on vasculature and dynamic aortic compliance are being investigated. Additional studies include evaluation of osteoarthritis and osteoporosis models, and interfacial problems associated with engineered biomaterials.

## Biomedical Materials

*Prof. Shivkumar*

Calcium phosphate ceramics for bone substitution. Biocomposites for cranio-maxillo-facial and orthopedic applications. Shape memory metals and polymers in biomedical devices. Fracture fixation devices. Degradation of implant materials. Interface mechanics issues between soft and hard connective tissues and engineered biomaterials. Structural and biological evaluation of new biomaterials via animal models.

## Ion Channels and Calcium Signals in "microdomains" of Single Cells

*Prof. Walsh*

Patch clamp technology allows the recording of ion current through a single gated pore (aka, an ion channel) in the surface membrane of the cell. When the pore, which is a single protein, opens, a current flows, and in this way the conformational

changes of a single protein can be studied in real time at a millisecond resolution. High speed imaging of calcium movements in small regions of a cell's interior can be monitored simultaneously at the same temporal resolution using imaging technology that employs calcium-sensitive dyes and a powerful optical system based on "star wars" technology. Combining these techniques allows the study of the function of small regions or microdomains in a single neuron or muscle cell. Since ion channels and calcium control a myriad of processes in all cells, new insights can be gained into cell function.

## Mechanoreceptor Neurons and Soft Tissue Biomechanics

*Profs. Grigg, Hoffman*

Research is focused on determining how the material properties of soft tissues influence the properties of mechanoreceptor neurons innervating them. *In vitro* preparations of skin and nerve, from gene-targeted mice, are subjected to dynamic biaxial loading *in vitro*. Tensile and shear stresses are controlled dynamically and biaxial strains are measured in real time. Measures of the skin's complex compliance are related to measures of the mechanical sensitivity of individual mechanoreceptor neurons.

## Medical Imaging

*Profs. King, Glick, Pretorius, and Gifford*

Modalities currently under investigation include single photon emission computed tomography, positron emission tomography, and computed tomography (CT). Within these modalities research is being performed on multi-dimensional tomographic image reconstruction, scatter and attenuation correction, restoration filtering, image segmentation, correction of respiratory and patient motion, observer comparison of image quality, and development of a CT mammography system. Currently research is mainly focused on clinical imaging, but a program in small animal imaging is anticipated to be initiated in the coming year.

## MRI-Based Computational Modeling for Carotid Plaque Rupture and Stroke

*Profs. Tang, Sotak, Hoffman*

The development of interdisciplinary bioengineering methods which combine computational modeling, Magnetic Resonance Imaging (MRI) technology, ultrasound/

Doppler technology (US), mechanical testing and histopathological analysis to analyze carotid atherosclerotic plaques, and to quantify critical blood flow and plaque stress/strain conditions under which plaque rupture is likely to occur. The long term goal is to automate the whole chain of accurate non-invasive data acquisition (MRI, US), advanced computational mechanical analysis, and reliable assessment of plaque vulnerability so that computational modeling and bioengineering techniques can be applied in diagnostic and clinical applications related to plaque rupture and stroke.

## 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.

## Rehabilitation Engineering

*Profs. Ault, Hoffman*

Research topics include the design and development of assistive devices and orthoses. Studies are also conducted on the effects of prostheses and orthoses on gait.

## Sensory and Physiologic Signal Processing

*Prof. Clancy*

Application of signal processing, mathematical modeling and other electrical and computer engineering skills to study the electrical activity of skeletal muscle (EMG). Applications include: improvements to the detection and interpretation of EMG amplitude for the control of powered prosthetic limbs, musculoskeletal modeling, clinical gait analysis and the assessment of muscular effort in industrial work tasks; and high-resolution surface EMG for non-invasive clinical and scientific decomposition of muscle fiber activation patterns.

## Spectroscopic Measurement of Blood and Tissue Chemistry

*Prof. Soller*

Applications of optical spectroscopy for the noninvasive measurement of blood and tissue chemistry, ultimately to be able to perform chemical analysis and diagnosis without removing a sample from the patient. Currently investigating the use of near infrared spectroscopy, in combination with in vivo chemometric techniques, to determine muscle pH, muscle oxygen tension and blood hematocrit. Applications of this technology are being investigated in the operating room, the emergency department and during exercise for astronauts in space.

## Ultrasound Measurements

*Prof. Pedersen*

Applications under current investigation include atherosclerotic plaque classification by means of ultrasound and ultrasound-based osteoporosis detection. For plaque classification, the goal is the development of an improved method for identifying atherosclerotic plaque types, especially distinguishing between stable and vulnerable plaque, by overcoming the aberrating effect of the inhomogeneous soft tissue layers between the transducer and the vessel. The concept is based on utilizing the detected backscatter level from a blood volume adjacent to the atherosclerotic lesion as a reference, in order to determine the absolute backscatter level of the lesion. For osteoporosis detection, the goal is to evaluate the efficacy of new ultrasound parameters for estimating bone density, microstructure and growth axis, as a basis of assessing fracture risk. In addition to BUA, new parameters are being investigated.

## Research Laboratories and Facilities

Research is primarily conducted in WPI's Salisbury Laboratories and on the University of Massachusetts Medical School (UMMS) campus. Core WPI biomedical engineering research laboratories include a biosensor and bioinstrumentation laboratory, a biomaterials/tissue engineering laboratory, and a soft tissue biomechanics/tissue engineering laboratory. Other research projects are conducted in the laboratories of associated biomedical

engineering program faculty at WPI and UMMS. Major areas of research focus in these laboratories include biomechanics, biological signal processing, imaging, tissue engineering and ultrasound. Cooperation with the Tufts University School of Veterinary Medicine makes their staff and facilities available for project work and internships.

A Nuclear Magnetic Resonance (NMR) imaging facility is located at the Central Massachusetts Magnetic Imaging Center (CMMIC) and is part of a joint research program between the Department of Biomedical Engineering and the Department of Radiology at the UMMC Center. This 1630-square-foot research facility houses a General Electric (GE) CSI-II 2.0 Tesla (T) / 45 cm imaging spectrometer as well as a chemistry/electronics laboratory for sample preparation and radio frequency coil research. In addition to the research facility, an 8500-square-foot clinical MR facility housing two GE 1.5 T clinical imaging instruments is available at the CMMIC for suitable research projects.

The Biomechanics and Tissue Engineering Laboratory is located on the WPI campus. The laboratory houses standard cell culture equipment (CO2 incubators, laminar hood, microscopes, etc.), biochemistry equipment (96 well plate reader, electrophoresis systems, gel imaging system, etc.), biomaterials synthesis capabilities, histology facilities, and custom mechanical stimulation and characterization devices.

In addition to the above research laboratories, the department maintains a number of teaching laboratories and facilities that may support research activities, including a bioinstrumentation and biosignals laboratory, a computing and imaging facility, a dedicated undergraduate projects laboratory and a physiology teaching facility. The department of biology and biotechnology, also located in the Salisbury Laboratories, maintains a number of facilities that also may support biomedical engineering research activities. The WPI Gordon Library provides complete library services. Access to other libraries in the Worcester area, including the UMMS medical library, is also available.

# Faculty

## Core BME Program Faculty

**C. H. Sotak**, Professor and Department Head; Ph.D., Syracuse University

**K. L. Billiar**, Assistant Professor; Ph.D., University of Pennsylvania

**G. R. Gaudette**, Assistant Professor; Ph.D., SUNY Stony Brook; cardiac biomechanics, myocardial regeneration

**Y. Mendelson**, Associate Professor; Ph.D., Case Western Reserve University

**R. A. Peura**, Professor; Ph.D., Iowa State University

**G. D. Pins**, Associate Professor; Ph.D., Rutgers University

## Associated BME Program Faculty

**Anderson, F. A., Ph.D.**; Department of Surgery, UMMS

**Ault, H. K., Ph.D.**; Department of Mechanical Engineering, WPI

**Camesano, T. A., Ph.D.**; Department of Chemical Engineering, WPI

**Carrington, W. A., Ph.D.**; Department of Physiology, UMMS

**Clancy, E. A., Ph.D.**; Department of Electrical and Computer Engineering, WPI

**Fogarty, K. E., M.S.**; Department of Physiology, UMMS

**Glick, S. J., Ph.D.**; Department of Radiology, UMMS

**Grigg, P., Ph.D.**; Department of Physiology, UMMS

**Hoffman, A. H., Ph.D.**; Department of Mechanical Engineering, WPI

**King, M. A., Ph.D.**; Department of Radiology, UMMS

**Lifshitz, L. M., Ph.D.**; Department of Physiology, UMMS

**Looft, F. J., III, Ph.D.**; Department of Electrical and Computer Engineering, WPI

**Ludwig, R., Ph.D.**; Department of Electrical and Computer Engineering, WPI

**Paydarfar, D., M.D.**; Department of Neurology, UMMS

**Pedersen, P. C., Ph.D.**; Department of Electrical and Computer Engineering, WPI

**Savilonis, B. J., Ph.D.**; Department of Mechanical Engineering, WPI

**Shivkumar, S. S., Ph.D.**; Department of Mechanical Engineering, WPI

**Singer, J. J., Ph.D.**; Departments of Physiology and Biochemistry and Molecular Pharmacology, UMMS

**Soller, B. R., Ph.D.**; Department of Anesthesiology, UMMS

**Sullivan, J. M., Ph.D.**; Department of Mechanical Engineering, WPI

**Tang, D.**, Department of Mathematical Sciences, WPI

**Tuft, R. A., Ph.D.**; Department of Physiology, UMMS

**Walsh, J. V., M.D.**; Department of Physiology, UMMS

**Wang, Y-L., Ph.D.**; Departments of Cell Biology and Physiology, UMMS

## Adjunct BME Faculty

**Helmus, A. E., Ph.D.**; Advance Nanotech

**Leal, M. J., M.S.**; U.S. Food and Drug Administration

**Rodger, R. M., D.V.M.**; Veterinarian, Private Practice

## 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 525. Microprocessor-Based Biomedical Instrumentation

This course provides hands-on laboratory experience with common biomedical transducers and instrumentation used in physiological and clinical evaluation. Lectures and laboratory experiments cover electronic circuit design and construction, analog/digital signal acquisition and processing, and microprocessor-based biomedical instrumentation. The basic principles of hardware and software designs for interfacing biomedical sensors to microprocessors are emphasized. (Prerequisite: Analog and digital electronics.)

### BME 541. Biological Systems

Review of control theory with applications to biological control systems. Development of mathematical models of selected biological control systems and the application of computer techniques in the simulation of these systems. (Prerequisite: Control engineering)

### 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 570. Engineering in the Clinical Environment**

Examines the responsibilities and functions of the biomedical engineer in the health care complex in the solution of the technical and engineering problems associated with patient care. Topics include equipment management, monitoring systems, electrical safety, prosthetics, technical education for medical personnel, hospital systems engineering and administrative functions.

### **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 ECE 3303 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 585. Principles of *In Vivo* Nuclear Magnetic Resonance Spectroscopy**

This course emphasizes the applications of Fourier transform nuclear magnetic resonance (FTNMR) spectroscopy in medicine and biology. Course topics include review of the basic physical concepts of NMR, review of covalent chemical binding and its relationship to the NMR chemical shift, factors in biological systems that influence the NMR chemical shift, data acquisition and processing techniques in vivo NMR spectroscopy, and the application of NMR spectroscopy to clinical studies. (Prerequisites: BME 582, organic chemistry and biochemistry are strongly recommended.)

### **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.

### **BME 595B. 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 595M. 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 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 I**

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 4025. Biomedical Instrumentation Design II**

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 biosensor interfacing, low-level measurements, analog-to-digital and digital-to-analog signal conversion, micro-processor- and microcontroller-based biomedical instrumentation, and programming. (Prerequisites: BME 2204 and BME 3011.) This course will be offered in 2005-2006, 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 2051, ES 2052, ME 3501, MA 2501].) This course will be offered in 2005-2006, and in alternating years thereafter.

### **BME 4541. Biological Systems**

Review of control theory with applications to biological control systems. Analysis and modeling of physiological systems. Physiological systems identification. Formulation of mathematical models of biological systems and the application of computer techniques in the simulation of these systems. (Prerequisites: Laplace transforms, transient response, frequency response and system stability analysis.) This course will be offered in 2005-2006, 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 2006-2007, 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 physicochemical 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 3130 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

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, and fuel cell technology. 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 produce impure 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.

### **Combustion-Generated Pollutants**

Approximately 50 tons of mercury is released into the atmosphere annually from coal combustion processes. Research is being conducted on understanding the chemical speciation of mercury, arsenic, and selenium in simulated combustion flue gases. Electron impact mass spectrometry is used to measure product concentration profiles of these species among flue gases containing chlorine, sulfur, nitrogen and water vapor. In addition, ab initio and density functional methods are being employed to gain understanding into the kinetic mechanisms involving these trace pollutants. Combining both experimental and theoretical techniques will allow for

a detailed and accurate picture of trace metal speciation in combustion flue gases, which will aid in the development of more effective control strategies. In addition, heterogeneous reactivity is being investigated through adsorption and surface reactions taking place on activated carbon and fly ash samples.

## **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, and 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 microporous and dense inorganic membrane synthesis, and reactive membrane studies, fouling and transport studies, characterization of membrane degradation and applications in biotechnology. Facilities including SEM with EDX and ultrafiltration units are available.

## Fuel Cell Center (FCC)

The Fuel Cell Center is a University/industry alliance comprising industrial members, faculty members, staff, and graduate and undergraduate students. The faculty members of FCC come from the various departments at WPI. The research is performed in the various laboratories of the faculty members. The industrial

members represent companies or other organizations with interest in fuel cell technology, including fuel cell companies, automobile manufacturers, utilities, petroleum companies, chemical companies, catalysis companies, etc.

The objectives of the FCC are: (1) to perform research and development of fuel cells, fuel reformers and related components for mobile and stationary applications; (2) to educate graduate and undergraduate students in fuel cell technology; and (3) to facilitate technology transfer between the University and industry. The current projects include development of proton-exchange membrane (PEM) fuel cells, direct methanol fuel cells (DMFCs), molten carbonate fuel cells (MCFCs), microbial fuel cells, fuel cell stacks, membrane reformers, microreformers, reformer catalysis, fuel cell electrocatalysis, composite proton-exchange membranes, inorganic membranes, and transport and reaction modeling.

## Faculty

**D. DiBasio**, Associate Professor and Department Head; Ph.D., Purdue University

**T. A. Camesano**, Associate Professor; Ph.D., Pennsylvania State University

**W. M. Clark**, Associate Professor; Ph.D., Rice University

**R. Datta**, Professor; Ph.D., University of California, Santa Barbara

**A. G. Dixon**, Professor; Ph.D., University of Edinburgh

**N. K. Kazantzis**, Associate Professor; Ph.D., University of Michigan

**Y. H. Ma**, Professor; Ph.D. Massachusetts Institute of Technology

**R. W. Thompson**, Professor; Ph.D., Iowa State University

**J. L. Wilcox**, Assistant Professor; Ph.D., University of Arizona

**H. S. Zhou**, Assistant Professor; Ph.D., University of California-Irvine.

### 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, adsorption, desorption and extraction. Multistaged separations. Principles and processes of some of the less common separations.

### CHE 574. Fluid Mechanics\*

Advanced treatment of fluid kinematics and dynamics. Stress and strain rate analysis using vectors and tensors as tools. Incompressible and compressible one-dimensional flows in channels, ducts and nozzles. Nonviscous and viscous flow fields. Boundary layers and turbulence. Flow through porous media such as fixed and fluidized beds. Two-phase flows with drops, bubbles and/or boiling. Introduction to non-Newtonian flows.

### CHE 580. Special Topics

This course will focus on various topics of current interest related to faculty research experience.

### CHE 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. 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 to enter the M.S. program. Students wishing to pursue the Ph.D. must follow the procedure described at left.

## Degree Requirements

Because graduate education in chemistry and biochemistry is primarily research oriented, there are no 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.

### Qualifying Examination

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

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 formally admitted to the Ph.D. program.

### Dissertation

An oral examination is held after candidates have submitted their dissertations. The faculty of the Chemistry and Biochemistry Department, at least one member of another department and other scientists are invited to participate. The examination generally consists of a brief oral presentation of the principal points of the dissertation by the candidate, followed by questions from the faculty. The scope of the examination may be broadened if the faculty feel it necessary. In addition, the candidate is required to present as a part of the thesis an original, significant proposal for further 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, regulation of plant development by light, and others.

- Molecular Design and Synthesis. Within this area there is active research on topics encompassing supramolecular materials, photovoltaic materials, polymorphism in pharmaceutical drugs, spectroscopy of heterocyclic molecules, photophysical properties of cumulenes, 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 Laboratories

The Chemistry and Biochemistry Department is located in Goddard Hall, which houses 20,000 square feet of research laboratories, shops and instrument laboratories. Department facilities and instrumentation in individual research laboratories that support this research include 200 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; 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

**J. W. Pavlik**, Professor and Interim Department Head; Ph.D., George Washington University; photochemistry of heteroaromatic compounds. Synthesis of deuterium labeled pprimidines and pyridazines for photochemical studies.

**J. M. Argüello**, Associate 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.

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

**J. MacDonald**, Assistant 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.

**V. R. Thalladi**, Assistant Professor; Ph.D., University of Hyderabad, India; organic and metal-organic materials; pharmaceutical polymorphism; organic and pharmaceutical alloys; porous, magnetic, and nonlinear optical materials; microfluidics.

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

## Course Descriptions

All courses are 3 credits unless otherwise noted.

### CH 502. Bioinorganic Chemistry

The subject matter of this course is bioinorganic chemistry, with emphasis on the application of physical methods to the study of active sites in bioinorganic systems. The physical methods discussed include magnetic susceptibility measurements, electronic absorption spectroscopy, resonance Raman spectroscopy, electron spin resonance, EXAFS and electrochemical techniques. Applications of these to a variety of metalloproteins including oxygen carriers (myoglobin, hemoglobin, hemocyanin), blue copper proteins, iron sulfur proteins, and low molecular weight structural and functional model systems are covered in detail.

### 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 531. Electronic Interpretation of Organic Reactions

Organic reaction mechanisms are interpreted in terms of "electron-pushing" rationalizations and elementary molecular orbital theory. The course involves a series of problem-solving discussion sessions.

### CH 533. Physical Organic Chemistry

Mechanisms of representative organic reactions and the methods used for their evaluation. Structural, electronic and stereochemical influences on reaction mechanisms.

### CH 534. Organic Photochemistry

Introduction to the photophysical and photochemical consequences of light absorption by molecules. Experimental techniques, excited state description, photochemical kinetics and energy transfer are among the topics discussed in relation to the primary photochemical reactions in simple and complex molecules.

### 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 539. Molecular Pharmacology

After a review of the pertinent aspects of human physiology, the course will focus on the variety of chemical messengers in the body, their storage release, action on target receptors and eventual fate. Discussion of endocrine receptors introduces the fundamental concepts of receptor-effector coupling, which are developed further in studies of the molecular structure and function of ion channels with application to the nerve impulse and of the acetylcholine receptors. Concepts of agonist and antagonist specificity, nonspecific blocking, drug addiction, etc. will be further developed in discussions of the catecholamines and the neuropeptides. Nonreceptor blocking will be further developed in a segment of ion co-transport systems in renal regulation. A knowledge of the material covered in one of the following is recommended: (1) CH 4110 and CH 4120, (2) BB 3100, or (3) CH 538, plus an understanding of protein and membrane structures.

### 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.

**CH 560 Current Topics in Biochemistry**

1 credit per semester

In this seminar course, a different topic is selected each semester. Current articles are read and analyzed.

**CH 561. Functional Genomics**

1 credit per semester

In this seminar course, students will present and critically analyze selected, recent publications in functional genomics. The course will conclude with a written project, either a mini-grant proposal or an analysis of publicly available data in a research manuscript format. The course will be offered in alternate years in lieu of CH 560, may be repeated as many times as offered, and satisfies the department's requirement for a graduate seminar in biochemistry.

**CH 571. Seminar**

0.5 credit per semester

Reports on current advances in the various branches of chemistry.

*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 master of science and doctor of philosophy in civil 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.

***Specialty programs are available 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 45).

The 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; 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; and water quality.

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, CE584, CE585 and ACC 501. (ACC 501 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 program 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 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.

Students with a B.S. in civil engineering may petition the department Graduate Program Committee to change the degree designation to an M.S. in civil engineering, if they so desire and are qualified.

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 master's degree and passed a qualifying admission examination. This examination is administered within the first 18 credits of registration in the Ph.D. program.

## **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.**

A dissertation in the candidate's major field of study is required. It is through the dissertation that a student demonstrates the ability to work independently on complex problems at a level commensurate with the Ph.D. degree. Since research interests of the civil and environmental engineering faculty are varied, there is opportunity for conducting research in several areas.

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, gas chromatograph, total organic carbon analyzer, UV-Vis spectrophotometer and particle counter. 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 (CE 4060 Environmental Engineering

Laboratory and CE 569 Environmental Engineering Treatability 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.

### **Geotechnical Laboratory**

The Geotechnical Laboratory is equipped for soil testing and is utilized for undergraduate teaching and projects and graduate research. The primary use of the laboratory is for teaching CE 4046.

### **Computer Laboratory No. 1**

Computer Laboratory No. 1 (2000 square feet, referred to as the Stat Lab because of its association with the Mathematics Department) contains 28 X-terminals connected to WPI's UNIX network system. This facility has a complete presentation system (with PC, computer projector, VCR and sound system). Primary use of this laboratory includes computer science and mathematics courses, civil engineering project work and open use by the WPI community.



## Computer Laboratory No. 2

Computer Laboratory No. 2 (2000 square feet, referred to as the CECIL Lab) contains 24 Pentium 400 computers connected to WPI's network system. In addition, hook-up jacks to network connections for laptop computers are provided at four large group tables in the center of the CECIL 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.

## Graduate Research Computing Laboratory (GRCL)

The GRCL is located in Kaven Hall, Room 203. The laboratory is for the use of civil and environmental engineering graduate students in the pursuit of their research and coursework. The GRCL contains the following equipment:

- 4 dual-processor Pentium computers (WindowsNT),
- 4 single-processor Pentium computers (Windows98),
- 1 Pentium computer with a digitizer pad,
- 1 Power PC with a scanner, and
- 1 HP LaserJet printer.

All the hardware is connected to the WPI network. The Civil and Environmental Engineering Department is continually adding hardware and software to this facility in support of research activities in the department.

## Faculty

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

**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**, Assistant Professor; Ph.D., University of Connecticut; industrial and domestic wastewater treatment, particulate processes in the environment, chemical oxidation of contaminants.

**D. S. Dutton**, Adjunct Assistant Professor; M.S., Worcester Polytechnic Institute.

**T. El-Korchi**, Professor; Ph.D., University of New Hampshire; glass fiber reinforced cement composites, tensile testing techniques, materials durability.

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

**W. F. Kearney**, Adjunct Assistant Professor.

**R. B. Mallick**, Assistant 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.

**F. Mulligan**, Adjunct Professor; M.S., Worcester Polytechnic Institute

**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; 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.

**J. K. Wakely**, Adjunct Associate Professor; B.S., University of Maine

## 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. Course may be offered by special arrangement.

### 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 512. Structural Stability Theory

Theory of elastic and inelastic buckling of beam columns and frames; lateral and torsional buckling of beams; buckling rings, arches and thin plates; buckling of shells; design equations and finite element methods in stability; bending of thin plates and shells. Use of microcomputers in stability problems. Course may be offered by special arrangement. (Prerequisite: differential equations, structural mechanics and matrix structural analysis will be assumed.)

### CE 519. Advanced Structural Analysis

Energy methods in structural analysis, concepts of force method and displacement methods, methods of relaxation and numerical techniques for the solution of problems in buildings, and long-span structures and aircraft structural systems. Effects of secondary stress in structures. Course may be offered by special arrangement. (Prerequisites: Structural mechanics and undergraduate courses in structural analysis, differential equations.)

### CE 523. Advanced Matrix Structural Analysis

Matrix methods of structural analysis, displacement and flexibility methods; substructuring, tall buildings, energy methods, finite elements, including plane stress and strain elements, approximate methods, solution of linear systems.

### CE 524/ME 533. Finite Element Method and Applications

See course description under ME 533.

### **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 533. Prestressed Concrete Structures**

Analysis and design of prestressed concrete structures. Linear prestressing, materials used in prestressed concrete, determinate and statically indeterminate prestressed concrete structures, connections, and shear and torsion. Design of tension and compression members and flat plates. (Prerequisite: A knowledge of undergraduate course in concrete design is necessary.)

### **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 537. Advanced Properties and Production of Structural Materials**

This course is particularly designed for civil engineers and will cover structure, properties and performance of construction materials. Topics include the structure of solids, phase equilibrium and reaction kinetics. A detailed analysis of mechanical properties and deterioration of solids will be presented. Theories and mathematical models based on these concepts will be applied to construction materials such as cementitious materials, bituminous materials, metals and alloys, timber, ceramics and composites. (Prerequisites: Structural mechanics, materials of construction, differential equations and computer literacy.)

### **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 544. Highway Safety Audits and Safety Management**

This course is an in-depth study of highway safety audit techniques as used in Europe and Canada, and safety management as used in the United States to identify and correct hazardous locations. Students will learn safety audit techniques through class work and a semester project where they perform a safety audit on an actual roadway. Topics include hazard and risk modeling, societal cost of collisions, performing a safety audit, recommending alternative solutions, quantifying safety benefits and prioritizing improvements. While there is no formal prerequisite, the course presumes a basic knowledge of undergraduate highway design as taught in CE 3050. The material covered in CE 543 is also useful background for this course. This course is usually offered in alternate spring semesters.

### **CE 550. Theoretical Soil Mechanics**

This course provides an advanced level study of theories of soil behavior and mechanics. The topics reviewed are physico-chemical factors affecting soil behavior, the effective stress principle, moisture migration, application of the theory

of elasticity to compute stresses in soil masses, settlement analysis, consolidation theory and geothermics. Appropriate laboratory and field testing procedures are discussed. Course may be offered by special arrangement.

### **CE 551. Theoretical Soil Mechanics II**

A continuation of CE 550. It addresses the nature of the strength-deformation characteristics of both rapidly and slowly draining soils. Stress path methods of analysis and critical state behavior models are emphasized. Elastic and plastic material failure theories are reviewed, and modern laboratory and field testing devices are described. Course may be offered by special arrangement.

### **CE 552. Earth Structures**

This course provides an in-depth study of the geotechnical principles applied to design of earth structures including earth dams, waste containment facilities, soil slopes, highway cuts, embankments and slurry trenches. It includes fundamentals of analysis of flow through porous media by graphical and digital techniques, slope stability, use of geosynthetics, soil stabilization, and the design of preloads and drain installations. Course may be offered by special arrangement.

### **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 5621. Open Channel Hydraulics**

This course begins with fundamentals of free surface flow, and includes engineering and environmental applications. Development of basic principles, including specific energy, momentum and critical flow. Rapidly varied, uniform and gradually varied steady flow phenomena and analysis. Density-stratified flow. Similitude considerations for hydraulic models. Optional topics: dispersion and heat transfer to atmosphere. Course may be offered by special arrangement.

### **CE 563. Industrial Waste Treatment**

Legislation; the magnitude of industrial wastes; effects on streams, sewers and treatment units; physical, chemical and biological characteristics; pretreatment methods; physical treatment methods; chemical treatment methods; biological treatment methods; and wastes from specific industries. Lab includes characterization and treatment of typical industrial wastes.

### **CE 565. 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 and CE 3069 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 579. Planning and Designing for a Sustainable Built and Natural Environment**

The planning and designing for a sustainable built and natural environment contrasts with the sprawl and resource use which is occurring presently. Sustainable development, whether it be an individual home, an office building, a neighborhood, a town/city, a region, or a nation, necessitates planning and designing with an understanding of social, economic and aesthetic factors, as well as impact on scarce and nonrenewable resources. A knowledge of the availability of limited resources, density assumptions and population demands, as well as future technology, and how these variables affect not only our present but also future generations—water resource availability, threatened species, global warming or infrastructure development—is critical to the civil engineer.

### **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 PRIMA-VERA 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.

## Program of Study

A specialization in computer and communications networks is available within the master's degree programs of the Computer Science (CS) and the Electrical and Computer Engineering (ECE) Departments.

Students enrolled in this specialization will receive the master of science degree in computer science or electrical and computer engineering, 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 or ECE 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 for ents.

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 or ECE 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 electrical engineering (ECE) and/or computer science (CS). Normally a B.S. degree in ECE or 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 department to which the student applies.

## Degree Requirements

### Computer Science

33 credits

### Electrical and Computer Engineering

33 credits for non-thesis; 30 credits for thesis

### 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/ECE 506)

### *and two of the following courses:*

- Telecommunications Transmission Technologies (ECE 535)
- High Performance Networks (CS 530/ECE 530)
- Advanced Computer and Communications Networks (ECE 537/CS 577)
- Modeling and Performance Evaluation of Networks and Computer Systems (CS 533/ECE 581)

## 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 (ECE 575/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/ECE 578)
- Advanced Cryptography (ECE 579R)
- Telecommunication Policy (ECE 508)
- Mobile Data Networking (ECE 539S)
- Any of the courses ECE 535, ECE 530/ CS 530, ECE 537/CS 577, and CS 533/ECE 581 not taken to satisfy the required courses above.

## CCN Project

The student must complete one of the following:

1. Computer and Communications Networks Internship (ECE 595/CS 595) (6 credits)  
This project requirement may be waived with documentation of relevant industrial experience. The waiver must be approved by the Graduate Program Committee of the student's department 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, or 30 credits for students in the ECE department completing a master's thesis. Courses may be chosen from relevant graduate-level courses in computer science, electrical and computer engineering, mathematics or management. Some students in the computer science degree program 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 and Electrical and Computer Engineering Departments, students in the CCN specialization must also satisfy all requirements of whichever computer science or electrical and computer engineering master's program they are enrolled in.

## Faculty

This is a joint specialization taught by computer science and electrical and computer engineering faculty.

## 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*) or master's degree in computer science, or with an equivalent background.

## 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

*i.e., 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 4241 Webware: Computational Technology for Network Information Systems
- CS 4341 Introduction to Artificial Intelligence
- CS 4432 Database Systems II
- CS 4513 Distributed Computing Systems
- CS 4514 Computer Networks: Architecture and Implementation
- CS 4515 Computer Architecture
- 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 501, CS 505, and CS 507

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 4123 Theory of Computation	CS 553	CS 553
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 4514 Computer Networks: Architecture and Implementation	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 second column. If an undergraduate course maps to a graduate course that satisfies a core area requirement for the MS degree, the undergraduate course satisfies that core area requirement. For example, a BS/MS student can satisfy the systems core area requirement for the MS by taking CS 4513 or CS 4514.

## Degree Requirements

### For the M.S.

These degree requirements are effective for all students matriculating after July 1, 2004. 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.

#### 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. The 33 credit hours must include at least one course from each of the core areas. Students should endeavor to take these required four courses as early as possible so as to provide the background for the remaining graduate work. 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. *IDG 501 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 at least one course from each of the core areas. Students should endeavor to take these required 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 up to two courses elected from other disciplines. *IDG 501 may not be counted towards the 33 credits required for a CS Master's degree.* To obtain a master's degree, all students must demonstrate graduate level competence in the following core areas of computer science. To satisfy each core area requirement, the student must satisfactorily complete at least one of the courses given in each core area. Students may petition the department to waive any core area requirement under special circumstances, but such action is strongly discouraged.

#### Core Areas

##### Theory

- CS 503 Foundations of Computer Science
- CS 521 Logic for Computer Science
- CS 559 Advanced Topics in Theoretical Computer Science

##### Algorithms

- CS 504 Analysis of Computations and Systems
- CS 524 Algorithms: Design and Analysis

##### Design

- CS 509 Design of Software Systems
- CS 536 Programming Language Design

##### Systems

- CS 502 Operating Systems
- CS 513 Introduction to Local- and Wide-Area Networks
- CS 529 Multimedia Networking
- CS 533 Modeling and Performance Evaluation of Network and Computer Systems
- CS 535 Advanced Topics in Operating Systems

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 core area requirements. 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.

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 take and perform acceptably on the Ph.D. qualifying examination, which includes both a written examination and a research component. Application to take the examination should be submitted to the department secretary at least two months prior to the examination date. The Ph.D. student is required to pass the examination prior to completing 36 Ph.D. credits.

Upon successful completion of the Ph.D. qualifying examination, 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 28 graduate credits, including 3 credits of graduate level mathematics.

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, artificial intelligence, computer vision, computer graphics, database and information systems, distributed systems, graph theory and computational complexity, network performance evaluation, programming languages, 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. The network backbone has 4 Gigabits of available bandwidth and offers high-speed connection to Internet2 via an OC-3 link to the Abilene network. Limited-access wired and wireless networking is available for research purposes. Other specialized resources include computing clusters, supercomputer access, Access Grid Node, and extremely large displays.

## 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

**E. O. Agu**, Assistant Professor; Ph.D., University of Massachusetts, Amherst

**D. C. Brown**, Professor; Ph.D., Ohio State University

**M. L. Claypool**, Associate Professor; Ph.D., University of Minnesota

**D. J. Dougherty**, Professor; Ph.D., University of Maryland

**D. Finkel**, Professor; Ph.D., University of Chicago

**K. Fisler**, Assistant Professor; Ph.D., Indiana University

**G. T. Heineman**, Associate Professor; Ph.D., Columbia University

**N. T. Heffernan**, Assistant Professor; Ph.D., Carnegie-Mellon University

**M. Hofri**, Professor; D.Sc., Technion-ITTT, Haifa, Israel

**R. E. Kinicki**, Associate Professor; Ph.D., Duke University

**K. A. Lemone**, Associate Professor; Ph.D., Northeastern University

**R. W. Lindeman**, Assistant Professor; Ph.D., The George Washington University

**M. Mani**, Assistant Professor; Ph.D., UCLA

**C. Ruiz**, Associate Professor; Ph.D., University of Maryland

**E. A. Rundensteiner**, Professor; Ph.D., University of California at Irvine

**G. N. Sarkozy**, Affiliate Associate Professor; Ph.D., Rutgers University

**S. M. Selkow**, Professor; Ph.D., University of Pennsylvania

**M. O. Ward**, Professor; Ph.D., University of Connecticut

**C. E. Wills**, Associate Professor; Ph.D., Purdue University

## 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 503. Foundations of Computer Science

The foundations of computer science are presented here. These form the basis for a more complete understanding of and proficiency in computer science. Topics include logic, computational models, formal languages, computability and complexity theory. (Prerequisite: undergraduate or graduate level discrete structures such as CS 2022, CS 501 or MA 2201.)

### 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 524 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 509. Design of Software Systems

This course focuses on the high-level design aspects of software engineering. Included are architectural and interface design. Within architectural design, the topics covered are Yourdan structured design, Jackson structured design and object-oriented design. When possible, real-time extensions are discussed. Sufficient coverage of the areas of requirements specification and testing is given to support the above topics. (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 524.)

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

See ECE 572 course description on page 65.

### **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 524. Algorithms: Design and Analysis**

This course covers the design, analysis and proofs of correctness of algorithms. Examples are drawn from algorithms for advanced data structures, set manipulation and searching, graphs and geometric problems. 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 data structures, discrete structures and algorithms.

*Note: students with a strong CS background in design and analysis of computer systems (at the level equal to a solid BS in computer science) should not take CS 524 and should consider taking CS 504.*

### **CS 525. Topics in Computer Science**

A topic of current interest is covered in detail. Please consult the department for a current listing of selected topics in this area. (Prerequisites: vary with topic.)

### **CS 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 generators, 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 504 or ECE 502 or equivalent background in CS 524.)

### **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 multi-processor systems and operating systems research. (Prerequisites: CS 502 and either CS 504, CS 524, or equivalent background in probability.)

### **CS 536. Programming Language Design**

This course discusses the fundamental concepts and general principles underlying current programming languages and models. Topics include control and data abstractions, language processing and binding, indeterminacy and delayed evaluation, and languages and models for parallel and distributed processing. A variety of computational paradigms are discussed: functional programming, logic programming, object-oriented programming and data flow programming. (Prerequisites: student is expected to know a recursive programming language and to have an undergraduate course in data structures.)

### **CS 538. Expert Systems**

The course will review expert knowledge-based problem-solving systems. It will concentrate on an analysis of the architecture, knowledge and problem-solving style of each system in order to classify and compare them. For each system, an attempt will be made to evaluate its contribution to our understanding of problems that expert 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 504 or CS 524 or permission of the instructor.)

### **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 549. Computer Vision**

This course examines current issues in the computer implementation of visual perception. Topics include image formation, edge detection, segmentation, shape-from-shading, motion, stereo, texture analysis, pattern classification and object recognition. We will discuss various representations for visual information, including sketches and intrinsic images. (Prerequisites: CS 534, CS 543, CS 545, or the equivalent of one of these courses.)

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

This course has an instructor-dependent syllabus.

### **CS 561. Advanced Topics in Database Systems**

This course covers modern database and information systems as well as research issues in the field. Topics and systems covered may include object-oriented, workflow, active, deductive, spatial, temporal and multimedia databases. Also discussed will be recent advances in database systems such as data mining, on-line analytical processing, data warehousing, declarative and visual query languages, multimedia database tools, web and unstructured data sources, and client-server and heterogeneous systems. The specific subset of topics for a given course offering is selected by the instructor. Research papers from recent journals and conferences are used. Group project required. (Prerequisites: CS 542 or equivalent. Expected background includes a knowledge of relational database systems.)

### **CS 562. Advanced Topics in Software Engineering**

This course focuses on the nondesign aspects of software engineering. Topics may include requirements specification, software quality assurance, software project management and software maintenance. (Prerequisite: CS 509.)

### **CS 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.)

### **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 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.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: communications and signal processing, computer engineering, electromagnetics and ultrasonics engineering, electronics and solid state, power engineering, and systems and controls.

## Admission Requirements

### M.S. Program

Students with a B.S. degree in electrical engineering or electrical and computer engineering may submit an application for admission to the M.S. program. Admission to the M.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 M.S. degree program in electrical and computer engineering. Contact the Graduate Coordinator for requirements, which will depend on the applicant's specific background.

Students 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. Contact the Graduate Coordinator for requirements, 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. 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.

## Degree Requirements

### For the M.S.

Students pursuing the M.S. degree may take either the nonthesis 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 taken at WPI. The remaining courses may be either at the 4000 (maximum of two) or the 500 level in computer science, physics, engineering or mathematics. The complete program must be approved by the student's advisor and the Graduate Program Committee.

### Program of Study

Regardless of the option chosen, each student must submit a program of study for approval by the student's advisor and the ECE Department Graduate Program Committee. To ensure that the Program of Study is acceptable, students should, in consultation with their advisor, submit it prior to the end of the semester following admission into the graduate program. Students must obtain prior approval from the 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

The M.S. thesis is required for students who are financially supported by the department in the form of teaching assistantship, research assistantship, or fellowship. M.S. thesis research involves 9 credit hours of work, registered under the designation ECE599, 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 other students, all students are encouraged to include a research component in their graduate program. A directed research project, registered under the designation ECE598, 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 (ECE599) to be applied toward a 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 BS/MS 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.

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 ECE699. The same academic standards as described in the M.S. guidelines apply to the doctor of philosophy program. A program of study form must be completed and approved.

The doctoral student must establish two minors in fields outside of electrical engineering. Physics, mathematics and computer science are usually recommended. Each student selects the minors in consultation with the major 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.

Full-time residency at WPI for at least one academic year is required while working toward a Ph.D. degree. This usually corresponds to the period of active dissertation research.

Satisfactory completion of the diagnostic examination and the area examination are required.

### **Diagnostic Examination**

The doctoral student is required to take the diagnostic examination during the first year beyond the M.S. degree (or equivalent number of credits, for students admitted directly to the Ph.D. program). Prior to taking this examination, a student must identify a faculty member who has indicated that he/she is willing to supervise the student's research. The purpose of the diagnostic exam is to determine if the student has the necessary foundation in mathematics and electrical and computer engineering to undertake doctoral studies. The diagnostic examination is composed of two parts: evaluation of basic knowledge and evaluation of research skills.

### **Evaluation of Basic Knowledge**

The examination covers fundamental concepts and selected advanced topics in electrical engineering. It is administered by the Graduate Program Committee. Students are examined in three areas: Engineering Mathematics and two areas to be selected from the following list by the student and faculty member supervising the student's research.

- Engineering Mathematics
- Signals and Systems
- Fields and Waves
- Power Systems
- Analog Circuits and Devices
- Digital and Computer Engineering
- Cryptography and Discrete Mathematics

The examination of basic knowledge is a written examination and is given yearly in January. The results from the exam will be graded Pass, Conditional Pass or Fail by the Graduate Program Committee. Students who receive the grade of Conditional Pass must fulfill conditions specified by the Graduate Program Committee in order to pass the examination. These conditions typically may include (but are not limited to) passing a course or courses with a specified grade, and/or retaking a portion of the examination the following year. No students will be permitted to take the exam or any portion of the exam more than twice.

A description of the material covered in each examination area and sample exam questions from previous years are available from the ECE Graduate Secretary.

### **Evaluation of Research Skills**

Upon passing the examination on basic knowledge of electrical engineering, satisfactory completion of one semester of directed research under a prospective Thesis Advisor is required. Specific guidelines for both the research skills proposal and the final research skills summary report are available from the department Graduate Coordinator.

Under no circumstances will a student be permitted to continue working toward the Ph.D. degree if he/she has failed either the written portion or the research portion of the diagnostic exam.

### **Area Examination**

The doctoral student is required to take the area examination before writing a dissertation. The examination, which deals with the student's research area, is administered by a committee consisting of the student's major advisor and other experts in the area of the student's research. Students who fail the examination may retake it at a later date with the approval of the ECE Graduate Program Committee. Upon passing both the Area

and Diagnostic examinations, the student's committee chair should submit notification of successful completion of candidacy requirements to the ECE Graduate Program Committee. Candidacy should begin at least eight months before the doctorate is to be granted.

### **Dissertation**

All Ph.D. students must complete and orally defend a dissertation prepared under the general supervision of the major advisor, who must be a full-time faculty member of the ECE department. The research described in the dissertation must be original and constitute a contribution to knowledge in the major field of the candidate. The Dissertation Committee normally serves as the Defense Committee as well and certifies the quality and originality of the dissertation research, the satisfactory execution of the dissertation and the preparedness of the defense. The Dissertation Committee consists of the major advisor (as committee chairperson) and at least two additional faculty members whose expertise will aid the student's research program. All members of the committee must hold doctoral degrees. At least two members of the committee must be full-time WPI ECE faculty, and at least one member must be from outside the student's department or from outside WPI. This committee will be selected by the student in consultation with the major advisor.

### **For the Combined B.S./Master's Program**

A WPI student accepted into the B.S./Master's program may use 6 credit hours of work for both the B.S. and M.S. degrees. Additional graduate credit hours of work (beyond the 15 units required for the B.S. degree) up to a total of 12 credit hours may be transferred from the student's undergraduate transcript. *All of these course credits must be defined prior to enrollment in the courses.*

A student must define the 12 credit hours at the time of applying to the B.S./Master's program. The 12 credit hours may be all advanced undergraduate courses, graduate courses, or combinations of both at the discretion of the student's advisor, subject to the approval of the ECE department Graduate Program Committee.

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 master's degree program. A copy of the student's transcript (grade report) must be included with the application.

A student who intends to complete the B.S./Master's program is required to be a full-time graduate student until the M.S. degree requirements are met. Any student who is accepted into the B.S./Master's program and who elects to finish the M.S. degree part time will be required to meet the normal, non-B.S./Master's program degree requirements.

## 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 a high-frequency network analyzer, spectrum analyzers, broadband RF amplifiers, and signal generators. Software systems supported include Ansoft HFSS antenna/EM simulator (multiple licenses). The laboratory is also equipped with other hardware tools to support antenna-related projects. The laboratory has been particularly active in the area of patch antenna design.

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

*Prof. Pahlavan*

This center is recognized as a pioneering facility in the important and rapidly growing area of wireless personal and data communications. The lab is supported by a broad range of networking and telecommunications corporations.

The work of CWINS is quite diverse. In recent years, basic research has been conducted in channel modeling and simulation, spread-spectrum techniques, adaptive equalization, multiple-access methods, network architectures, wireless optical communications, microstrip antennas and RF circuit design. The lab has been particularly active in the measurement of indoor RF propagation.

### 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 multi-media, 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.

### Center for Sensory and Physiologic Signal Processing – C(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.

## Lightwave Nanophotonics Device Engineering Laboratory (LOVElab)

*Prof. King*

Researchers in the LOVElab are primarily concerned about developing the cutting-edge theory and experimental work to enable the creation of a new generation of nanoscale optical devices that will dramatically advance the state-of-the-art in optical computing and high-speed optical networks. Current research topics pursue a variety of novel photonic crystal structures to support the lab's mission. For example, we are investigating resonant structures that preserve the quantum state of an optical pulse with a nearly arbitrary temporal delay. The delay is tuned electro-optically. We are also investigating the effects of incorporating nano-electro-mechanical systems (NEMS) inside photonic crystals to dynamically control the light-matter interaction. Applications include non-linear frequency conversion, tunable lasers, optical routing, and dynamic optical add/drop filters. The LOVElab staff is also continually improving upon finite-difference-time-domain algorithms to accurately simulate and characterize the response of the nanoscale devices.

Our laboratory is currently equipped with two optical tables as well as the standard assortment of fiber and free-space optical components. High-performance computational simulation computers are also available to aid in the analysis of the proposed devices and theories.

MS thesis and PhD dissertation topics are available for motivated students interested in joining the pursuit of this exciting new frontier of electrical engineering, optics, and physics.

## Power Electronics and Power Systems Laboratory

*Profs. 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 Ultrasound Research Lab is engaged in several critical endeavors in medical imaging: The team is developing a wearable untethered lightweight ultrasound scanner that is voice command controlled, uses head mounted display, and has wireless upload of images. Such a scanner may be used in military medicine, for rural health and in emergency medicine. The wearable imaging system is being further developed with three-dimensional (3D) ultrasound capabilities, by use of position and angle sensors, so that not only anatomical slices can be observed, but whole organs or lesions or vessels can be observed as a 3D object, with possibility for volume estimation. Another effort is in tissue boundary detection, for expanding the 3D applications. Other efforts involve the design of ultrasound phantoms in which injuries such as abdominal bleeding and collapsed lung can be emulated, and development of non-invasive technique for detection of the vulnerable plaque, that is, arterial plaque which has a high risk of leading to a stroke.

The Ultrasound Research Laboratory has office space for graduate students and research space for ultrasound experiments, numerical modeling work, and development of electronic circuits. The lab has medical ultrasound scanners, modified for research purposes. Ultrasound pulser/receivers and measurement tanks are available, including a scanning tank with stepper motor controlled positioning system for the ultrasound measurements. The lab is well equipped with computers and general instrumentation.

## Cryptography and Information Security (CRIS) Laboratory

*Prof. Sunar*

The CRIS Laboratory conducts research and development in cryptography and its applications. One research focus is fast

implementations of the next generation of public-key algorithms such as elliptic and hyperelliptic curve schemes. We work on fast software algorithms and efficient hardware architectures. The lab is equipped with industry-standard development tools for ASIC and FPGA target hardware. We also apply Xilinx FPGAs and Altera EPLDs to new types of cryptosystems, which allow for a fast switch of private-key encryption algorithms ("algorithm agility").

Another research focus is the integration of cryptography and data security into new communication networks. We work on the design and implementation of security protocols for wireless networks, with an emphasis on wireless LANs. Another network type of interest is the high-speed Asynchronous Transfer Mode network. We investigate system design and algorithmic issues.

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>.

## Faculty

**Fred J. Looft**, Professor and Department Head; Ph.D., Michigan. Instrumentation, digital and analog systems, signal processing, biomedical engineering, microprocessor systems and architectures, space-flight systems.

**Donald R. Brown**, Assistant 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; Ph.D., Polytechnic Institute of Brooklyn. Application of control and estimation theory to electric power systems, reliability evaluation of electric power systems.

**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.

**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.

**Michael Gennert**, Associate Professor; Sc.D., MIT. Computational vision, image processing, scientific databases, artificial intelligence, programming language semantics.

**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.

**Brian M. King**, Assistant Professor; Ph.D., University of Arizona. Nanoscale optical engineering, optical communication, error-correction codes.

**H. Peter D. Lanyon**, Professor Emeritus; Ph.D., University of Leicester.

**Wenjing Lou**, Assistant 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**, Associate 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; Dean of Undergraduate Studies; 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. Wireless integration of portable ultrasound systems, 3-ultrasound visualization, tissue characterization

with ultrasound; atherosclerotic plaque classification; modeling and optimizing pulse-echo ultrasound systems; ultrasound methods for assessing bone microarchitecture.

**Robert A. Peura**, Professor; Ph.D., Iowa State University, 1969. Biomedical instrumentation and biosensors; noninvasive measurement of blood glucose and urea; impedance imaging and spectroscopy.

**L. R. Ram-Mohan**, Professor; Ph.D., Purdue University. Field theory, many-body problems, solid-state physics, and finite-element modeling of quantum systems.

**John M. Sullivan Jr.**, Professor; D.E., Dartmouth College, 1986. Design of computer-aided engineering systems, development of graphics tools and mesh generation, numerical analysis of partial differential equations.

**Berk Sunar**, Assistant 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 Project Center, and Director of the Limerick, Ireland, Project Center; Ph.D., Worcester Polytechnic Institute. Technological education reform, internationalization of higher education, project-based education, sustainable design and appropriate technology.

## 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, control-lability, 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 queueing analysis and network programming. (Prerequisites: A knowledge of the C programming language is assumed. CS 504 or ECE 502 or equivalent background in probability; may be taken concurrently. NOTE: Students who receive credit for ECE 573 may not receive credit for ECE 506.)

### **ECE 508. Telecommunications Policy**

This course provides an understanding of some of the major trends and issues involved in the development of U.S. telecommunications and information technology policies. The course highlights the interaction between technology and policy; it will help engineers to accept the reality that, in the introduction of new technologies, policy considerations often play a more important role than do technological advances. The course traces the historical development of U.S. telecommunications policy from supporting a regulated monopoly to the creation of the current increas-

ingly more competitive and less regulated information marketplace. Topics explored include: the difficulties involved in assessing newly emerging technologies; regulation and deregulation of the telecommunications and information industries; the past, present and future concept of universal service; the convergence of telecommunications, computer and television technologies to create the information network of the future; current competition in local, long-distance, wireless and multimedia services; issues related to standards, interoperability and intellectual property.

### **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 measurements 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 501 Modern Signal Analysis, 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 introduction to the design of analog and mixed analog-digital CMOS integrated circuits for communication and instrumentation applications. An overview of the CMOS fabrication process shows the differences between discrete and integrated circuit design. The MOS transistor is 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 MOS 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 CMOS process. Examples of possible topics include sample-and-hold (S/H) amplifier, analog-to-digital (A/D) and digital-to-analog (D/A) converters, phase-locked loop (PLL), voltage-controlled oscillator, phase detector, switched capacitor and continuous-time filters, and sampled current techniques. (Prerequisite: Background in analog circuits both at the transistor and functional block [op-amp, comparator, etc.] level. Also familiarity with techniques such as small-signal modeling and analysis in the s-plane using Laplace transforms. Undergraduate course equivalent background ECE 3204; ECE 4902 helpful but not essential.)

### **ECE 529. Selected Topics in Electronic System Design**

Courses in this group are devoted to the study of advanced topics in electronic system design.

### **ECE 529B. Analog Circuits and Intuition**

The ability to see the simplicity in a complex design problem is a skill that is not usually taught in engineering classes. Some engineers, when faced with design problems, immediately fill up pages and pages of calculations, or do complex circuit simulations or finite-element analyses. One problem with this approach is that if you get an answer, you don't know if it is correct unless you have an intuitive "feel" for what the answer should be. The application of some simple rules-of-thumb and design techniques is a possible first step to developing intuition into the behavior of complex electrical systems. This course outlines some ways of thinking about analog circuits and systems that are intended will help to develop intuition and guide design. The lectures are a mixture of instructional sessions covering new background material, and design case studies. (Prerequisites: Undergraduate background in device physics, microelectronics, control systems, electromagnetism)

### **ECE 529C. Noise in Analog and Mixed Signal Circuits and Systems**

This course covers the application of probabilistic techniques to the analysis of noise in analog and mixed signal circuits and systems, as well as the design of systems to meet required noise performance. The course begins with a review of basic and advanced probability concepts: probability, random variables, stochastic processes, power spectral density, and autocorrelation. This is followed by a description of fundamental noise mechanisms (e.g. thermal noise, shot noise) and noise models at the device level for the MOS-FET and bipolar transistors. Modeling of noise at the amplifier and system level, as well as noise

simulation in SPICE, is also covered. These noise analysis techniques are then applied to the design of low noise amplifiers, for both discrete and integrated circuit applications. Also addressed are interference mechanisms that affect measured noise performance, including crosstalk, power-supply induced noise, and ground loops. The course concludes with optional advanced topics, possibly including  $1/f$  noise, phase noise and jitter in oscillators, and phase-locked loops (PLL) systems. (Prerequisite: Undergraduate courses in probability, signals and systems, analog microelectronics. ECE 502 helpful but not essential.)

### **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 queuing 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 532. Digital Communications: Modulation and Coding**

Studies various modulation techniques and coding schemes for digital communications over additive white Gaussian noise channels. Overview of communication networks, and relation to link design and modem design technology. Representation of bandpass signals. Binary and  $M$ -ary signaling, basic modulation techniques: PSK, FSK, PAM, QAM and MSK. Timing and phase recovery. Introduction to information theory, source coding and channel coding. Signaling with coded waveforms, soft decision and hard decision block codes, convolutional codes and Trellis Code Modulation. Characterization of time-dispersive band-limited channels and intersymbol interference (ISI). (Prerequisite: ECE 502.)

### **ECE 533. Advances in Digital Communication**

Methods for ISI reduction: linear, decision feedback, pass band and fractionally spaced equalizers; maximum likelihood sequence estimation (MLSE). Fast start-up equalization, blind equalization and echo-cancellation. Characterization of fading multipath channels such as troposcatter, HF, microwave line-of-sight, urban and indoor radio. Digital signaling over fading multipath channels. Methods to improve performance in fading multipath channels: diversity combining,

coding and equalization. Introduction to spread spectrum communication: code division multiple access, performance in fading channels. Multiple access techniques in radio networks. (Prerequisite: ECE 532 or equivalent).

### **ECE 535. Telecommunications Transmission Technologies**

This course introduces the principal 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**

Topics from the following: sensitivity and error analysis in linear systems; band-limited signals; the uncertainty principle; bandwidth compression, nonstationary processes; radio and inter-symbol interference. Current problems in digital and analog communications; two-dimensional Fourier analysis; pattern recognition; Fourier optics. Time-series analysis, radar signals, graph theory and information theory. The content of this course will change from year to year.

### **ECE 539S. Mobile Data Networking**

This course presents the principles of wireless data communications by introducing the state-of-the-art network architectures, standards and products, and explaining the key factors in evolution of this industry. Overview of wireless networks. Architecture of existing mobile data networks: ARDIS, Mobitex, TETHRA, Mercicom, CDPD and GPRS. Wireless LAN technologies: 802.11, HIPERLAN and wireless ATM. Effects of mobility on different ISO layers. Physical layer options. MAC layer in mobile environments. Issues in mobile computing. Mobile IP, IP-v6, and DHCP. Mobility gateway technologies: MASE and eNetwork. Intertech roaming and handover for wireless data networks. (Prerequisite: Familiarity with communication networks [ECE 506 or similar] is desirable.)

### **ECE 545/CS 545. Digital Image Processing**

See CS 545 course description.

### **ECE 549. Selected Topics in Control**

Courses in this group are devoted to the study of advanced topics in the formulation and solution of theoretical or practical problems in modern control.

### **ECE 559. Selected Topics in Energy Systems**

Courses in this group are devoted to the study of advanced topics in energy systems. Typical topics include optimal power flow, probability methods in power systems analysis, surge phenomena, design of electrical apparatus, transient behavior of electric machines and advanced electromechanical energy conversion.

### **ECE 566. VLSI Design**

VLSI Design introduces computer engineers and computer scientists to the techniques, methodologies and issues involved in conceptual and physical design of complex, digital integrated circuits. The course presupposes knowledge of computer systems and hardware design such as found in ECE 505, but does not assume detailed knowledge of transistor circuits and physical electronics. (Prerequisite: ECE 505 or equivalent.)

### **ECE 569. Selected Topics in Solid State**

Courses in this group are devoted to the study of advanced topics in solid state, for example: degenerate semiconductors, many-body theory, elastic effects and phonon conduction, and solar cells. To reflect changes in faculty research interests, these courses may be modified or new courses may be added.

### **ECE 569A Advanced Solid-State Devices**

The operation of the MOS transistor will be explored in detail, resulting in thorough understanding of observed phenomena. Device behavior will be explained using the energy band diagram and modeled for large and small signals as well as high frequencies. Sources of noise, subthreshold operation, scaling effects, and other non-ideal behavior will also be addressed. While the MOS transistor will be the focus of the course, advanced topics in bipolar transistor design may also be included. This course is intended for students pursuing study in either integrated circuit design or device physics. (Prerequisite: undergraduate analog electronics)

### **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** 3 credits

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 into the field of cryptography and data security. The course begins with the introduction of the concepts of data security, where classical algorithms serve as an example. Different attacks on cryptographic systems are classified. Some pseudo-random generators are introduced. The concepts of public and private key cryptography are developed. As important representatives for secret key schemes, DES and IDEA are described. The public key schemes RSA and ElGamal, and systems based on elliptic curves are then developed. Signature algorithms, hash functions, key

distribution and identification schemes are treated as advanced topics. Some advanced mathematical algorithms for attacking cryptographic schemes are discussed. Application examples will include a protocol for security in a LAN and a secure smart card system for electronic banking. Special consideration will be given to schemes which are relevant for network environments. For all schemes, implementation aspects and up-to-date security estimations will be discussed. (Prerequisites: Working knowledge of C; an interest in discrete mathematics and algorithms is highly desirable. Students interested in a further study of the underlying mathematics may register for MA 4891 [B term], where topics in modern algebra relevant to cryptography will be treated.)

### **ECE 579. Selected Topics in Computer Engineering**

Courses in this group are devoted to the study of advanced topics in computer engineering such as real-time intelligent systems, VLSI design and high-level languages.

### **ECE 579R. Advanced Cryptography**

This course provides deeper insight into areas of cryptography which are of great practical and theoretical importance. The three areas treated are detailed analysis and the implementation of cryptoalgorithms, advanced protocols, and modern attacks against cryptographic schemes. The first part of the lecture focuses on public key algorithms, in particular ElGamal, elliptic curves and Diffie-Hellman key exchange. The underlying theory of Galois fields will be introduced. Implementation of performance security aspects of the algorithms will be looked at. The second part of the course deals with advanced protocols. New schemes for authentication, identification and zero-knowledge proof will be introduced. Some complex protocols for real-world application—such as key distribution in networks and for smart cards—will be introduced and analyzed. The third part will look into state-of-the-art cryptoanalysis (i.e., ways to break cryptosystems). Brute force attacks based on special purpose machines, the baby-step giant-step and the Pohlig-Hellman algorithms will be discussed. (Prerequisites: ECE 578/ CS 578 or equivalent background.)

### **ECE 579S. Computer Security**

This course provides a comprehensive introduction to the field of computer security. Security architectures and their impact on computers are examined. Critical computer security aspects are identified and examined from the standpoints of both the user and the attacker: physical security, communications security, system security and operational security. Computer system vulnerabilities are examined, and mitigating approaches are identified and evaluated. Concepts and procedures for computer and computer network risk analysis are introduced. An overview of computer security

statutes and case law is presented. The course emphasizes a timely approach, maintained by using recent examples of computer attacks and the resources available to deal with the rapidly changing framework of computer security. (Prerequisites: Working knowledge of computers, basic computer networks and a programming language.)

### **ECE 579T. Network Security**

This course provides a comprehensive introduction to the field of network security. Network architectures and protocols and their impact on security are examined. Critical network security aspects are identified and examined from standpoints of both the user and the attacker. Network vulnerabilities are examined, and mitigating approaches are identified and evaluated. Concepts and procedures for network risk analysis are introduced. Integration of network and computer security is introduced. An overview of statutes and case law affecting network security is presented. The course emphasizes a timely approach, maintained by using recent examples of network vulnerability. (Prerequisites: Working knowledge of computers, basic computer networks, computer security, and a programming language.)

### **ECE579U Information Security Systems and Management**

This course addresses the essential elements of turning individually secure workstations and networks into a secure information system. An engineering view of how overall security can be obtained in the face of individual system elements that are only partially secure will be undertaken. Risk identification, vulnerability assessment, disaster planning and recovery, continuity of operations, and interactions of large computer networks will be discussed. Essential information on pertinent laws and regulations will be included, as will an introduction to computer forensics. A viable systems security design and supporting security policy will be developed. (Prerequisites: ECE 579S, 579T)

### **ECE 579V. Computer Arithmetic Circuits**

Computer arithmetic is a subfield of digital computer organization. It deals with the hardware realization of arithmetic functions to support various computer architectures, as well as with arithmetic algorithms for hardware implementation. A major focus of computer arithmetic is the development of high-speed arithmetic algorithms, design of application-specific circuits to enhance the speed of numerical applications, and understanding their implementation in ASIC technology. This course consists of a detailed study of the theory, specification and design of basic arithmetic algorithms and hardware architectures used in digital systems. Topics that will be covered include: number systems and representation, redundant and residue systems. Addition/subtraction circuits, multiplication, division, square-root-finding algorithms, and floating point arithmetic systems.

### **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 595/CS 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 in the program.)

### **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.)

### **ECE699 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.

## 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. GRE scores are required for all international students and strongly recommended for all others.

Students with science degrees and graduates of some engineering disciplines may be required to take selected undergraduate courses to round out their backgrounds.

Applicants for the doctor of philosophy in fire protection engineering should have strong academic backgrounds in any of a host of engineering or science disciplines, and should submit samples of scholarly writing.

## 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, see page 16, or 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, wildfire phenomena, 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, standard flame spread apparatus, 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, and flame spread model development.

## 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.

**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

**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. R. Barnett**, Professor; Ph.D. WPI; Mathematical modeling and computer simulation of fires in buildings, ships and transit systems with an emphasis on heat transfer in structures and structural

behavior; the use of computers in fire investigation and fire reconstruction; fire fighter safety

**N.A. Dembsey**, Associate 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

**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

**B.J. Meacham**, Adjunct Associate Professor; Ph.D., Clark University; risk and public policy, performance-based design, risk concepts in regulation, uncertainty in egress modeling

**F. Noonan**, Associate Professor; Ph.D., University of Massachusetts; operations risk management, decision/risk analysis, environmental management

**M. T. Puchovsky**, Adjunct Assistant Professor; 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

**G. Proulx**, Adjunct Associate Professor, Ph.D., University of Montreal; human factors studies in emergency situations; evacuation procedures, egress behaviour, response to alarm signal, communication system, photoluminescent wayguidance system, wayfinding, safety for people with special needs

**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

**J.P. Woycheese**, Assistant Professor; Ph.D., University of California Berkeley; fire, smoke, and brand modeling, teaching technology from development of multimedia collections to visual representation of concepts and experimental data, fire protection systems, including water mist-fire interactions,

**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 and ceiling jets, 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 563/OIE 541. Operations Risk Management**

See OIE 541 course description.

### **FPE 565. Firesafety Engineering Evaluation**

This course develops techniques to evaluate the firesafety performance of a variety of facilities of the built environment and to produce management plans for decision making. The framework for this course is a firesafety engineering method which decomposes the firesafety system into discrete elements suitable for quantitative evaluation using a variety of fire protection engineering and fire science materials. (Prerequisites: FPE 521, FPE 553 and FPE 570.)

### **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 product 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 574/CM 594. 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.)

### **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.

### **FPE 580P. Fire and Materials**

In the modern era (and more so in the future) fire engineers have a need to simulate fire growth using tools such as CFAST and FDS. How to do this correctly will set the context for this course. How to properly characterize the fire behavior of combustible materials via appropriate parameters or "effective properties" is the main topic of this

course. Methodologies for characterizing materials ranging from fire dynamics based indexing to varying complexity pyrolysis models will be studied. Appreciation for empirical techniques needed to characterize materials will be introduced via lab demonstrations and exercises involving modern fire testing apparatuses. Students will start with the raw test data and learn how to develop appropriate parameters or "effective properties" for the methodology of interest

Prerequisites: FPE 521 and computational skill with Excel, Matlab, or equivalent. Basic numerical and statistical methods will be used in the course and students are responsible for learning these methods on their own as assigned. Familiarity with CFAST and FDS is helpful but not required.

### **FPE 580Q. Combustion**

This class is intended to provide an engineer with the basic understanding of various combustion phenomena. It will begin by covering fundamental governing equations for reacting flow, chemical kinetics, and mechanisms of hydrocarbon oxidation. The theory of deflagrations and detonations will be studied. The course will touch briefly on themes of combustion diagnostics, environmental issues, and power generation. Emphasis will also be given on the recent research interest on micro-scale combustion applications. The primary goal of the class is to provide students with tools and understanding to solve the basic problems in combustion, and to enable them to read and understand the literature in this broad field of study.

### **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 592. FPE Business Practice** 3 credits

This course requires the student to demonstrate the capability to integrate advanced fire safety science and engineering concepts into the professional practice environment. The work may be accomplished by individuals or small groups of students working on the same project. This practicum requires the student to prepare professional quality technical reports, business plans, proposals, project budgets, and timelines, and make oral presentations to communicate the results of their work.

### **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 master's programs to meet new professional needs or the special interests of particular students.

## Interdisciplinary Ph.D. Programs

Interdisciplinary Doctoral 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 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 toward the doctorate.

If the CGSR approves the proposal, the sponsoring group serves in place of a department in establishing specific degree requirements beyond those of the university, in advising, in preparing and conducting examinations, and in certifying fulfillment of degree requirements.

WPI and the University of Massachusetts Medical School have developed a joint doctoral program in biomedical engineering and medical physics. See page 30.

The Social Science and Policy Studies department offers an interdisciplinary doctoral program in Systems Modeling in collaboration with the Mathematical Sciences, Electrical and Computer

Engineering, Computer Science, Civil and Environmental Engineering, and Mechanical Engineering departments. The SSPS Department also offers an interdisciplinary Ph.D. in Social Science. See page 112.

## Interdisciplinary Master's Programs

Interdisciplinary master's programs may include a thesis or project requirement and require at least 30 credits beyond the bachelor's degree. 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 and 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.

Current Interdisciplinary Master's degree programs include:

- MS in Systems Modeling
- MS in Construction Project Management
- Impact Engineering
- Manufacturing Engineering Management
- Power Systems Management
- 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 a least some of their professional time to college-level teaching. The Certificate in College Teaching program offers an opportunity to acquire both teaching skills and professional recognition of high-level preparation to teach.

The Certificate represents a collaborative institutional response to the ever-present challenges of promoting exemplary teaching in today's complex higher education environments. Most college professors are never trained to be teachers. Preparation for the college classroom involves more than a solid base of knowledge in a discipline; it requires a systematic inquiry into the pedagogies and processes that facilitate learning. Our certificate program is grounded in the latest educational research of best practices in college teaching, and is designed to enhance the teaching and learning experiences for faculty and students at our member institutions.

The primary focus of the Certificate is to prepare graduate students and adjunct faculty for a career in academia. Research has shown that graduate students with some formal preparation in college teaching have a substantial advantage in the academic job market. Once hired, the new faculty members are better prepared to assume their teaching duties and are, consequently, more productive in developing



their research programs. Similarly, more experienced college faculty can also benefit from such teaching certificate programs, as they may be very well prepared in their disciplines, but desire formal training in the pedagogy of teaching.

### **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 costs of \$250/credit for graduate students approved by their department head to participate. 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.

## 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.

## Master of Business Administration (MBA)

WPI's MBA program features a 15-credit core of five cross-functional courses designed to give students a larger framework for understanding disciplinary material that is critical for managers in a globally competitive technological world. Core courses include:

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

Each core course, with the exception of Legal and Ethical Context of Technological Organizations, has prerequisite requirements from within an 18-credit foundation. The purpose of the foundation is to ensure that students have a solid understanding of the basic functions carried out in organizations and of the environment in which they operate as well as an introduction to the tools used to analyze business problems. Foundation courses consist of the following nine 2-credit courses, each of which covers a major functional area of business:

- ACC 501 Financial Accounting
- FIN 502 Finance
- FIN 508 Economics of the Firm
- FIN 509 Domestic and Global Economic Environment of Business
- MIS 507 Management Information Systems
- MKT 506 Principles of Marketing
- OBC 503 Organizational Behavior
- OIE 504 Operations Management
- OIE 505 Quantitative Methods

Foundation-level courses are potentially waivable based on prior graduate or undergraduate coursework.

The MBA program also features a capstone Graduate Qualifying Project (BUS 516) 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.

## 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 9 required courses:

- MIS 507 Management Information Systems
- MIS 571 Database Applications Development
- MIS 573 Systems Design and Development
- MIS 577 Foundations of Information Technology
- MIS 578 Telecommunications Management
- OBC 503 Organizational Behavior
- OBC 511 Interpersonal and Leadership Skills for Technological Managers
- OIE 504 Operations Management
- OIE 513 Designing Processes for Technological Organizations

Students then choose from one of six different three-course concentrations in the field of information technology. These concentrations provide additional depth in particular areas of IT, or IT management,

beyond the core courses. Students can choose a more managerial specialty, a more technical specialty, or specialties that mix management and technology or focus on a specific functional area. Concentration areas include:

- IT Project Management
- IT and Entrepreneurship
- IT Applications Development
- Information Security Management
- Marketing IT Applications
- Manufacturing and Service IT Applications

To round out the program, students take a minimum of 2 free elective credits, choosing any graduate management course to complete their program.

### **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 14 credit hours of required coursework including:

- FIN 508 Economics of the Firm
- MKT 506 Principles of Marketing
- MKT 512 Creating and Implementing Strategy in Technological Organizations
- OBC 503 Organizational Behavior
- OBC 511 Interpersonal and Leadership Skills for Technological Managers
- OIE 505 Quantitative Methods.

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

- BUS 597 Internship
- BUS 598 Independent Study
- ETR 592 New Venture Management and Entrepreneurship
- 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 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 the following 5 courses:

- MIS 507 Management Information Systems
- OBC 503 Organizational Behavior
- OBC 511 Interpersonal and Leadership Skills for Technological Managers
- OIE 504 Operations Management
- OIE 552 Modeling and Optimizing Processes

Students then select 7 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
- OBC 531 Managing Organizational Change
- OBC 533 Negotiations
- OIE 513 Designing Processes for Technological Organizations
- 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 3 elective courses (9 credit hours) from the approved list

Process Design Track:

- OIE 513 Designing Processes for Technological Organizations
- OIE 541 Operations Risk Management
- OIE 555 Lean Process Design
- OIE 557 Service Operations Management
- OIE 558 Designing and Managing Six-Sigma Processes
- Plus 2 elective courses (6 credit hours) from the approved list

To round out the program, students take a minimum of 2 free elective credits, choosing any graduate management course to complete their program.

### **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 Department of Management. 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
- SS 1110 Introductory Microeconomics
- SS 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.

49 credits, prior to waivers, distributed as follows (credit in parentheses):

- **9 Foundation Courses** (or graduate/undergraduate equivalents)  
ACC 501, FIN 502, FIN 508, FIN 509, MIS 507, MKT 506, OBC 503, OIE 504, OIE 505, (2 credits each)
- **5 Core Courses**  
ACC 514 (4 credits), BUS 515 (2 credits), MKT 512 (3 credits), OBC 511 (3 credits), OIE 513 (3 credits),
- **Graduate Qualifying Project (GQP)**  
BUS 516 (4 credits)
- **4 Elective Courses** (12 credits)

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

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

- **9 Required Courses**  
MIS 507 (2 credits), MIS 571 (3 credits), MIS 573 (3 credits), MIS 577 (3 credits), MIS 578 (3 credits), OBC 503 (2 credits), OBC 511 (3 credits), OIE 504 (2 credits), OIE 513 (3 credits)
- **3 Course Concentration** (all courses 3 credits each)

#### IT Project Management:

MIS 576, OBC 531, Choose one of: MIS 574, OBC 533

#### IT and Entrepreneurship:

ETR 592, MIS 579, Choose one of: MKT 563, OIE 546

#### IT Applications Development:

MIS 574, MIS 579, Choose one of: MIS 576, OBC 531

#### Information Security Management:

MIS 582, OIE 541, Choose one of: MIS 574, MIS 579, OIE 558

#### Marketing IT Applications:

MKT 568, Choose two of: MIS 574, MIS 579, MKT 563, MKT 567, OIE 546

#### Manufacturing and Service IT Applications:

MIS 574, Choose two of: OIE 544, OIE 553, OIE 555, OIE 557

- **2 credits (minimum), any graduate management course.**

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

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

- **6 Required Courses**  
FIN 508 (2 credits), MKT 506 (2 credits), MKT 512 (3 credits), OBC 503 (2 credits), OBC 511 (3 credits), OIE 505 (2 credits)
- **6 Elective Courses** (3 credits each)  
Selected from the following:  
BUS 597, BUS 598, BUS 599, ETR 592, MIS 576, MIS 578, MIS 579, MKT 563, MKT 564, MKT 567, MKT 568, OBC 531, OBC 533, OBC 535, OIE 546, OIE 548

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

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

- **5 Required Courses**  
MIS 507 (2 credits), OBC 503 (2 credits), OBC 511 (3 credits), OIE 504 (2 credits), OIE 552 (3 credits)
- **7 Elective Courses** (3 credits each)  
Students may select 7 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, OBC 531, OBC 533, OIE 513, 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 3 elective courses from the previous list.

### Process Design Track:

OIE 513, OIE 541, OIE 555, OIE 557, OIE 558, Plus 2 elective courses from the previous list.

- **2 credits (minimum), any graduate management course.**

## Department Research

In addition to teaching, Management Department 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 Department of Management, 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. C. Banks**, Professor and Department Head; 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.

**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.

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

**J. J. Mistry**, Assistant Professor; D.B.A., Boston University; intersection of information technology and management accounting.

**K. Mukherjee**, Assistant Professor; Ph.D., University of Connecticut; efficiency and productivity analysis applied to manufacturing, banking, and other sectors.

**M. Nilsson**, Assistant Professor; Ph.D., Stockholm School of Economics; corporate finance, corporate governance, law and finance, international finance.

**F. Noonan**, Associate Professor; Ph.D., University of Massachusetts; operations management, decision/risk analysis, environmental management.

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

**J. Schaufeld**, Visiting Instructor of Entrepreneurship; MBA, Northeastern University; entrepreneurship, technology commercialization, business acquisition and development.

**D. Strong**, Associate 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**, Assistant 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.

**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.

**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 501. Financial Accounting

2 credits

This course is an introduction to the accounting process, its underlying concepts, and the techniques of preparing and analyzing financial statements. Students are introduced to issues in accounting for assets, liabilities and stockholders' equity, and issues in revenue and expense recognition. The course demonstrates the role of accounting information for users outside the firm, and the application of accounting numbers in financial analyses and market decisions. Where appropriate, emphasis is given to technology-oriented firms.

### 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 515. Legal and Ethical Context of Technological Organizations

2 credits

This course introduces students to U.S. and International law, examining the structure, function and development of the areas of law most important to the conduct of business. Heavy emphasis is given to approaches to ethical analysis for decision-making. Students will gain a sound understanding both of the basic areas of law (torts, contracts, property and constitutional law) and of the analytical principles that govern the application of law generally. The course will also touch on the areas of intellectual property law, business formation and organization, international business law, securities regulation, cyber law and e-commerce, antitrust law, employment law and environmental law. The course focuses on practical considerations and makes extensive use of case studies. In addition to analyzing the legal mandates that restrict and guide the conduct of business, the course discusses and debates ethical considerations that often confront managers.

### BUS 516. Graduate Qualifying Project In Management (GQP)

4 credits

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, which 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: All foundation and core courses or equivalent content, or consent of instructor.)

### 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 Department of Management. 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 592. New Venture Management and Entrepreneurship

Entrepreneurship has been defined as the "pursuit of opportunity without regard to resources currently held." This course is intended to introduce students to a new way of thinking (the pursuit of opportunity) and a new set of economic relationships (without regard to resources currently held) through its requirement that they plan and launch a new e-commerce venture. Topics will include opportunity recognition and evaluation, new venture teams, the business plan, venture finance and resource requirements, and harvesting the venture.

### 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 System Design And Development 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.

### MIS 507. Management Information Systems

2 credits

This course focuses on information technology and management. 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).

### **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 and MIS 577, 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 577. Foundations of Information Technology**

This course introduces students to the foundations of information technology and the concepts and principles of visual, object-oriented techniques for the development of business applications. Students will use commercial, computer-based development tools and rapid development and prototyping techniques for the design of small business applications for such areas as customer tracking, order processing, and financial analysis.

### **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 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 506. Principles of Marketing**

2 credits

This course provides the background by which managers may understand consumer and industrial decision-making. Topics covered include segmentation and target marketing, market research, competitor analysis and marketing information systems. Additional discussion focuses on the development of a marketing plan and positioning of the product. Attention is also paid to product management, new product development, promotion, price and distribution. Both national and global aspects of these issues are discussed.

### **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.

**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 503. Organizational Behavior**

2 credits

This course introduces concepts, theories and current research in the effective management of organizations. Topics include the basics of systems thinking, as well as team and group dynamics. The role of perception and motivation in the behavior of the individual is addressed. Cases, workshops and readings are integrated in a cohesive approach to management problems.

**OBC 511. Interpersonal and Leadership Skills for Technological Managers**

This course considers effective interpersonal and leadership behaviors in technological organizations. Course material focuses on understanding, changing and improving our behaviors and those of others by examining our own practices and analyzing examples of leadership behaviors. The course also considers interpersonal and leadership behaviors in relation to teams, cultural diversity, and ethics in organizations. Assignments may include personal experiments, case analyses, individual and group projects and/or presentations. (Prerequisite: OBC 503 or equivalent content, or consent of instructor.)

**OBC 531. Managing Organizational Change**

This course focuses on the design and implementation of organizational change. The course will look at organizations from a variety of theoretical perspectives and consider the implications for change from each perspective. Students will engage in and discuss case studies, simulations, and experiential exercises to explore the subject.

**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.

**OIE 504. Operations Management**

2 credits

This course provides students with a broad conceptual framework for evaluating operations management practices and understanding the major decisions made in operations and the connections of operations decisions to other functions. Concepts, techniques, and management tools related to the four major decision responsibilities of operations management, namely process, quality, capacity, and inventory, are studied and discussed.

**OIE 505. Quantitative Methods**

2 credits

This course provides the background by which a modern manager may understand and apply quantitative methods. Topics covered include descriptive state, probability theory, measures of dispersion and hypothesis testing, and confidence descriptions. Additional discussion focuses on correlation and regression analysis, as well as analysis of variance and time series mathematics as applied to business analysis.

**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.

**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

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 WPI faculty has passed new requirements for the MS degree in MFE. The new requirements allow for considerably more flexibility in selecting the courses to satisfy the core. A student who satisfies the previous requirements will also satisfy the new ones. Any one course can only be used to satisfy distribution in one area.

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 seven 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 seven 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*

## 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 seven 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.

## 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.

## 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.

**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) model-

ing 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.

**R. S. Hahn**, Visiting Research Scientist; Ph.D., University of Cleveland

**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 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.

**Yong-Mo Moon**, Assistant Professor; Ph.D., University of Michigan, 2000; Mechanisms and reconfigurable machinery design, design methodology, control, and mechanisms design.

**F. Noonan**, Associate Professor of Management; Ph.D., University of Massachusetts

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

**A. Zheng**, 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.)

### **MFE 594A/ME 594. Computer-aided Tooling**

The objective of this course is to provide a fundamental knowledge of manufacturing tooling and computer-aided fixture design, to enhance the design and analysis capabilities in manufacturing tooling areas, and to gain the problem solving skill. This course starts from reviewing the fundamental knowledge of manufacturing processes and fixture design principles, and continues with introducing the newly developed computer-aided fixture design and analysis technologies. Laboratory study of modular fixture assembly, software practice and development, and a project will be included. The course is project-based and research oriented.

### **MFE 594P. Advanced Manufacturing Processes and Systems**

The objective of this course is to provide an in-depth knowledge of manufacturing processes, including machining, grinding, and forming processes. A system approach will be used in class to integrate the science, engineering and management studies into the processes. The emphases will be on the quantitative analysis and control of the processes with modeling and analyzing the relationship of production performance and crucial process parameters. Quality assurance and cost analysis are the integral part of the modeling and analysis. The course consists of lectures, lab practice, plant tour, and a course project. Recommended background: ME 1800 Manufacturing Processes, ME 3901 Experimentation, and ES 3011 Control.

### **MFE 594T. Surface Metrology: Measurement and Analysis of Surface Textures**

This course examines the methods for measuring and analyzing surface texture (roughness) in order to make functional correlations between the texture and performance, and to improve the understanding of texture-dependent surface phenomena like adhesion, scattering, fracture, friction and wear. Selection of surface measurement instruments and analysis methods, including fractal-based analysis, for finding functional correlations, quality control and the design of surface textures will be discussed. Examples from a broad range of applications will be discussed, including skin, run-ways, thermal spray adhesion, hard disks, machining and grinding.

### **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 594N 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 thermo gravimetric analyzer (TGA), a corrosion laboratory, topographic analysis laboratory and machining force dynamometry. A range of materials processing, fastening, joining, welding, machining, casting and heat treating facilities is also available.

## Admission Requirements

The program is designed for college graduates with engineering, mathematics or science degrees. Some undergraduate courses may be required to improve the student's background in materials science and engineering. For further information, see page 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 Engineering Laboratories

This industry-sponsored laboratory supports particulate processing research by materials science and manufacturing students and faculty. The laboratory is equipped with a variety of powder prepa-

ration, processing and characterization equipment, as well as equipment for green body consolidation and sintering. Equipment includes, cold press, various sintering furnaces (capable of up to 1700°C in air and controlled atmospheres), a differential thermal analyzer, X-ray sedimentograph, and equipment for electrical property and density measurements.

### **Mechanical Testing Laboratory**

Experimental mechanical testing laboratories are available for teaching and research related to mechanical properties and deformation of metals, ceramics, and composite materials. Equipment available includes: two computer-controlled Instron 8502 Servo-Hydraulic Tension-Compression Systems with supporting grips, environmental chambers, and furnaces; an Instron Model 4201 computerized tensile tester for high-accuracy, low-load testing of ceramic materials; an ASCERA hydraulic tensile tester for brittle materials; two high-temperature and three room-temperature stress-rupture systems.

### **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.

### **Optical and Electron Metallography Laboratories**

One scanning electron microscope (SEM), a transmission electron microscope JEOL 100CX II (TEM), optical reflection and transmission microscopes, and supporting sample preparation and photographic equipment are the major facilities available for microstructural analysis. The JSM840 (SEM) is equipped with stage-

automated digital image analysis, a light element (Uranium down to Boron) Quantum X-Ray detector with a KeveX Delta system, and a wavelength dispersive X-ray analyzer. These facilities are used primarily for micro-structural analysis and determination of crystal structures of fine phases present in metals and ceramics.

### **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. The characterization parameters should have clear physical interpretations for understanding the mechanisms which control surface behavior and surface creation. The laboratory has also been utilized in specialized image analyses, used, for example, to characterize the internal morphology of ceramic membrane.

### **X-Ray Diffraction Laboratory**

Two fully automated and computerized X-ray diffractometers are available for teaching and research: a GE-XRD-5 diffractometer and a Nicolet 12/V polycrystalline diffraction system. In addition, a variety of software has been developed to utilize these instruments effectively. Currently, background modeling, peak searching and curve fitting with deconvolution are in use for quantitative phase analysis and residual stress analysis. A search of the JCPDS Powder Diffraction File is provided with the Nicolet system. A variety of X-ray cameras and goniometers are available along with choice of x-ray tube targets to provide a wide X-ray diffraction capability. Additional support software is shared with the electron microscopy facility to generate diffraction patterns for any crystal system, in any desired orientation.

### **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)
- The Morris Boorky Powder Metallurgy Research Center (PMRC)

### 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-five 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 workshops, 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 50 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.

### The Morris Boorky Powder Metallurgy Research Center (PMRC)

The center addresses the scientific, engineering and managerial problems of the powder metallurgy industry. By integrating facilities from different disciplines, the center has developed research programs in engineering and management, addressing new technologies as well as methodologies for their implementation, i.e., valve creation and management issues in a small, fragmented industry. The objectives of the PMRC are as follows:

- Establish an educational and research center for the powder metallurgy industry, and provide a vehicle for manufacturing excellence and competitiveness of the industry.
- Establish long-term relationships between the academic community and members of management, manufacturing and research in the industry.
- Develop for graduate and undergraduate students course and project experiences that will foster an understanding of the industry.

Twenty-one corporate members participate and support the PMRC research programs. Project opportunities, industrial internships, co-op opportunities and summer employment are available through PMRC/MPI.

### 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.

**R. F. Bourgault**, Professor Emeritus; M.S., Stevens Institute of Technology

**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. 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**, Research Assistant Professor; 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; elasticity; small and long crack growth behavior; fracture mechanics; fatigue life prediction models, powder metallurgy.

**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., WPI. Solidification of Metals, the application of heat, mass and momentum transfer to modeling and solving engineering materials problems, and processing of ceramic materials.

**Md. Maniruzzaman**, Research Assistant Professor; Ph.D., WPI. Mathematical and computer modeling in materials processing, mechanical and microstructural characterization and materials processing.

**Q. Pan**, Research Associate Professor, Northwestern Polytechnic University. Semi-solid metal processing, aluminum casting and alloy characterization, molten aluminum handling and processing, grain refinement of aluminum alloys, fracture and fatigue.

**S. Shivkumar**, Professor; Ph.D., Stevens Institute of Technology. Biomedical Materials, Plastics, Materials 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. 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, microbial 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 D term 2007.

**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 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 2006.

**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.

**MTE 594P/ME 489P. Analysis and Control of Materials Processes**

The fundamentals of the processing-structure-property-performance relationships for casting, powder metallurgy, heat treating and coating manufacturing processes will be developed. The fundamental relationships between the process parameters and the specifications will be examined in terms of process control requirements and process capability. Process parameter measurement and control strategies will also be discussed. The course will include team projects and industrially supplied problems. Recommended background: ES 2001 Introduction to Materials, ME 2820 Materials Processing.

**MTE 594N/ME 489N. Introduction of 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 and nano-optics. Recommended background: ES 2001 Introduction to Materials, ME 2820 Materials Processing.

**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. Of particular note are the statistical consulting course, which develops interpersonal and statistical consulting skills, and the master's project, which involves the solution of a large-scale real-world problem, often originating in industry, business or government.

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 from 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 analysis, 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.

For teachers in the Massachusetts public schools, WPI may grant a professional license upon completion of the MME degree.

## 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 and either

teacher certification in mathematics or science or a full-time teaching position in one of these disciplines. Students are encouraged to enroll in courses on an ad hoc basis without official program admission. However, these students will not be eligible for any financial aid and must pay full tuition for each course. A typical student would complete the program in two years, taking one course each semester. However, the program can accommodate other completion schedules as well.

## 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 courses numbered 503 or higher. 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. 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 Master's Degree Program in Financial Mathematics is a 30-credit-hour program including a 3-credit-hour professional M.S. project originating from the financial industry. Students must take foundation courses MA 503 and MA 540, at least three from the four core financial mathematics courses MA 571, MA 572, MA 573 and MA 574, and two additional electives chosen from the graduate courses offered by the Mathematical Sciences Department.

A 6-credit block has to be completed in one of the following complementary areas outside of the Mathematical Sciences Department: financial management (e.g., from ACC 501, FIN 502 or FIN 509), information technology (e.g., from MIS 571, MIS 573 or MIS 578) or computer science (e.g., from CS 504, CS 531, CS 534, CS 542 or CS 552). Students with a degree or substantial work experience in one of the above complementary areas can substitute other courses for them subject to prior approval by the departmental Graduate Committee. B.S./Master's students can count undergraduate credits for MA 4213, MA 4235, MA 4237, MA 4473 or MA 4632 toward electives and suitable undergraduate courses toward the complementary area requirement.

Students shall participate in the Professional Master's Seminars MA 562A and MA 562B. The Professional M.S. Project MA 598 involves solving a real-life problem originating in the financial industry. A student's Plan of Study and the topic of the master's project require prior approval by the departmental Graduate Committee.

### 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 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, ME 531 and ME 532;
- 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 507 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.

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 course per semester, 3 semesters per year.

### 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**, Visiting Assistant Professor; 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.

**C. G. Burgos**, Visiting Assistant Professor; Ph.D., University of the Philippines - Los Baños, 2002; Bayesian inference, analysis of survey data, poverty estimation.

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

**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.

**R. S. Kim**, Assistant Professor; Ph.D., Harvard University, 2005; biostatistics, statistical methodologies for genomic data.

**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 stopping (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 dynam-

ics, preconditioned iterative methods for linear and non-linear problems, numerical partial differential equations, mixed and non-conforming finite methods, overlapping non-matching grids, mortar finite elements, eigenvalue solvers, aeroelasticity, porous media reservoir modeling.

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

**D. Tang**, Professor; Ph.D., University of Wisconsin, 1988; biofluids, biosolids, blood flow, mathematical modeling, numerical methods, scientific computing, nonlinear analysis, computational fluid dynamics.

**D. Vermes**, Associate Professor; Ph.D., University of Szeged, Hungary, 1975; optimal stochastic control theory, nonsmooth analysis, stochastic processes with discontinuous dynamics, adaptive optimal control in medical decision making.

**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.

**J. Wilbur**, Assistant Professor; Ph.D., Purdue University, 2002; applied statistics, resampling methods, multivariate statistical analysis, model selection, Bayesian inference, statistical issues in molecular biology and ecology

**J. S. Williford**, Visiting Assistant Professor; Ph.D., University of Delaware, 2005

**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 503-504. Analysis I and II

Topics covered include open and closed sets, compactness, continuity, upper and lower semicontinuity, Lebesgue measure, integration, functions of bounded variation, absolute continuity, the fundamental theorem of calculus for Lebesgue integrals, Banach spaces, classical  $L^p$  spaces, the Hölder and Minkowski inequalities, the Riesz-Fischer theorem, and the Riesz representation theorem. (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, Gauss mean value theorem, maximum modulus theorem, Rouché's theorem, 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 instructor and students. Examples are: planetary orbit, 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.)

### **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 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 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 and MA 504.)

### **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 530. Discrete Mathematics/CS 501. Discrete Structures**

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 application of the theory to real data using statistical computer packages. (Prerequisite: knowledge of basic probability and statistics at the level of MA 511 is assumed.)

### **MA 547. Design and Analysis of Observational and Sampling Studies**

Like controlled experiments, observational studies seek to establish cause-effect relationships, but unlike controlled experiments, they lack the ability to assign treatments to observational units. Sampling studies, such as sample surveys, seek to characterize aspects of populations by obtaining and analyzing samples from those populations. Topics from observational studies include: prospective and retrospective studies; overt and hidden bias; adjustments by stratification and matching. Topics from sampling studies include: simple random sampling and associated estimates for means, totals, and proportions; estimates for subpopulations; unequal probability sampling; ratio and regression estimation; stratified, cluster, systematic, multistage, double sampling designs, and time permitting, topics such as model-based sampling, spatial and adaptive sampling. (Prerequisite: knowledge of basic probability and statistics, at the level of MA 511 is assumed.)

### **MA 548. Quality Control**

This course provides the student with the basic statistical tools needed to evaluate the quality of products and processes. Topics covered include the philosophy and implementation of continuous quality improvement methods, Shewhart control charts for variables and attributes, EWMA and Cusum control charts, process capability analysis, factorial and fractional factorial experiments for process design and improvement, and response surface methods for process optimization. Additional topics will be covered as time permits. Special emphasis will be placed on realistic applications of the theory using statistical computer packages. (Prerequisite: knowledge of basic probability and statistic, at the level of MA 511 is assumed.)

### **MA 549. Analysis of Lifetime Data**

Lifetime data occurs frequently in engineering, where it is known as reliability or failure time data, and in the biomedical sciences, where it is known as survival data. This course covers the basic methods for analyzing such data. Topics

include: probability models for lifetime data, censoring, graphical methods of model selection and analysis, parametric and distribution-free 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**

Introduction to arbitrage-based pricing of derivative securities, and their uses for hedging and risk management. Topics include securities markets, futures, options, swaps and other derivatives; arbitrage and risk-neutral pricing; binomial trees, martingales, stochastic difference equations; Black-Scholes formula and partial differential equation via limit transition; pricing of American options, convertible bonds, options on dividend-paying stock and on futures; sensitivity measures ("greeks"), implied and estimated volatilities; use of derivatives for hedging and risk management.

### **MA 572. Financial Mathematics II**

This course introduces the advanced mathematical concepts and terminology used at the professional quantitative financial workplace and in the literature, and provides students with the background necessary to work in the rapidly expanding fixed income securities sector. The first part of the course is devoted to the concepts, terminology and methods of continuous-time mathematical fi-

nance. Topics include Brownian motion, continuous-time martingales. Stochastic differential equations, Ito calculus; risk-neutral valuation in terms of equivalent martingale measures. The power of the new tools is demonstrated on the derivation of the Black-Scholes and foreign exchange option pricing formulas. The second part of the course is devoted to fixed income securities and the term-structure of interest rates. Topics covered in this part include fixed income markets, instruments, risks and the term structure of interest rates; yield curve models, calibration and fitting; pricing of interest rate derivatives using models based on short rates (Vasicek, Cox-Ingersoll-Ross), and on the static and dynamic term-structure of interest rates (Ho-Lee, Black-Derman-Toy, Hull-White and Heath-Jarrow-Morton); pricing of corporate bonds, mortgage-backed securities and insurance-linked bonds; implementation of pricing models; derivative strategies for hedging and risk management in the fixed income sector. (Prerequisites: MA 503, MA 540 and MA 571.)

### **MA 573. Computational Methods of Financial Mathematics**

Most realistic financial derivatives models are too complex to allow explicit analytic solutions. The computational techniques used to implement those models fall into two broad categories: finite difference methods for the solution of partial differential equations (PDEs) and Monte Carlo simulation. Accordingly, the course consists of two 7-week blocks covering the following topics.

**Part I:** Parabolic PDEs, Black-Scholes PDE for European and American options; binomial and trinomial trees; explicit, implicit and Crank-Nicholson finite difference methods; far boundary conditions, convergence, stability, variance bias; early exercise and free boundary conditions; parabolic PDEs arising from fixed income derivatives; implied trees for exotic derivatives, adapted trees for interest rate derivatives.

**Part II:** Random number generation and testing; evaluation of expected payoff by Monte Carlo simulation; variance reduction techniques—antithetic variables, importance sampling, martingale control variables; stratification, low-discrepancy sequences and quasi-Monte Carlo methods; efficient evaluation of sensitivity measures; methods suitable for multifactor and term-structure dependent models. (Prerequisites: MA 571, undergraduate level familiarity with numerical methods and basic programming skills.)

### **MA 574. Portfolio Valuation and Risk Management**

Balancing returns vs. risks is one of the fundamental tasks of quantitative financial management. This course presents the most important mathematical concepts, methods and models used to value assets; select, maintain and optimize portfolios; and to manage risks. Topics covered include the following: returns, risks and utilities; quantification of risk—variance, shortfall risk, value at

risk; portfolio analysis, diversification, correlations, principal components, sensitivity measures ("greeks"); asset valuation and pricing methods as capital markets theory, capital asset pricing model, efficient frontiers, arbitrage pricing theory, consumption/accumulation and equilibrium models; risk management techniques—diversification, immunization, insurance/reinsurance, hedging; optimal asset allocation, portfolio optimization and dynamic delta hedging. The quantitative techniques covered in this course are used to support decisions by trading desk managers, corporate investment strategists, mutual companies, utilities, and of companies with commodities or foreign exchange risk exposures. (Prerequisite: MA 571.)

### **MA 590. Special Topics**

Courses on special topics are offered under this number. Contact the Mathematical Sciences Department for current offerings.

### **MA 595. Independent Study** 1 to 3 credits

Supervised independent study of a topic of mutual interest to the instructor and the student.

### **MA 596. Master's Capstone** 1 or more credits

The Master's Capstone is designed to integrate classroom learning with real-world practice. It can consist of a project, a practicum, a research review report or a research proposal. A written report and a presentation are required.

### **MA 598. Professional Master's Project** 1 or more credits

This project will provide the opportunity to apply and extend the material studied in the coursework to the study of a real-world problem originating in the industry. The project will be a capstone integrating industrial experience with the previously acquired academic knowledge and skills. The topic of the project will come from a problem generated in industry, and could originate from prior internship or industry experience of the student. The student will prepare a written project report and make a presentation before a committee including the faculty advisor, at least one additional WPI faculty member and representatives of a possible industrial sponsor. The advisor of record must be a faculty member of the WPI Mathematical Sciences Department. The student must submit a written project proposal for approval by the Graduate Committee prior to registering for the project.

### **MA 599. Thesis** 1 or more credits

Research study at the master's level.

### **MA 698. Ph.D. Project** 1 or more credits

Ph.D. project work.

### **MA 699. Dissertation** 1 or more credits

Research study at the Ph.D. level.

## Mathematics for Educators

### MME 518. Geometrical Concepts

This course focuses primarily on the foundations and applications of Euclidean and non-Euclidean geometries. The rich and diverse nature of the subject also implies the need to explore other topics, for example, chaos and fractals. The course incorporates collaborative learning and the investigation of ideas through group projects. Possible topics include geometrical software and computer graphics, tiling and tessellations, two- and three-dimensional geometry, inversive geometry, graphical representations of functions, model construction, fundamental relationship between algebra and geometry, applications of geometry, geometry transformations and projective geometry, and convexity.

### MME 522. Applications of Calculus

2 credits

There are three major goals for this course: to establish the underlying principles of calculus, to reinforce students' calculus skills through investigation of applications involving those skills, and to give students the opportunity to develop projects and laboratory assignments for use by first-year calculus students. The course will focus heavily on the use of technology to solve problems involving applications of calculus concepts. In addition, MME students will be expected to master the mathematical rigor of these calculus concepts so that they will be better prepared to develop their own projects and laboratory assignments. For example, if an MME student chose to develop a lab on convergence of sequence, he/she would be expected to understand the rigorous definition of convergence and how to apply it to gain sufficient and/or necessary conditions for convergence. The process of developing these first-year calculus assignments will enable the MME students to increase their own mathematical understanding of concepts while learning to handle mathematical and computer issues which will be encountered by their own calculus students. Their understanding of the concepts and applications of calculus will be further reinforced through computer laboratory assignments and group projects. Applications might include exponential decay of drugs in the body, optimal crankshaft design, population growth, or development of cruise control systems.

### 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  $\mathbb{R}^n$  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; and 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 queueing.

### 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' 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.

### Aerospace Laboratory

This laboratory includes a closed circuit, subsonic wind tunnel. This facility with a test section cross-section of 2' x 2' is capable of speeds up to 60 mph. The laboratory includes a hot-wire anemometry system ultrasonic acoustic instruments, as well as ancillary laboratory equipment. Additionally, workshop areas are provided for model preparation and smaller scale experiment development.

### Computational Fluid and Plasmadynamics Lab (CFPL)

CFPL is a modern computational facility in HL236 that includes workstations, a Linux cluster for high performance computing, peripherals and data storage devices. CFPL has access to Direct Simulation Monte Carlo, Particle-in-Cell, fluid dynamics, and MHD codes as well as visualization and data reduction software. Standard software also include MatLab, FLUENT for single and multi-phase CFD, and FEMLAB for investigation of problems with linked, multiple mode physical processes. Research conducted in CFPL entails the development and application of numerical simulation methods to spacecraft propulsion and micro-propulsion, spacecraft power, space environment/spacecraft interactions, micro-fluidics, nano-fluidics, and fluid/structure interactions. The Satellite Tool Kit (STK) and FreeFlyer are also available for spacecraft orbital analysis.

### Fluid Dynamics Laboratory

This laboratory provides experimental facilities and instrumentation for activities in the area of fluid dynamics. A small, open-return subsonic wind tunnel, hot wire anemometry system, computer data acquisition systems and high-speed flow visualization systems are available. Separate areas are provided for model preparation and small-scale experiments.

## **Fluid and Plasmadynamics Lab (FPL)**

The FPL consists of several vacuum chambers and specialized test facilities in HL314 and HL016 for the investigation of plasma thruster, electrospray sources (for both propulsion and nano-fabrication applications), plume/spacecraft interactions and microfluidic devices. 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  $10^{-6}$  Torr range. This chamber is used primarily for study of electrospray sources.

A 50-inch diameter, 72-inch long stainless steel vacuum chamber, scheduled to be complete in the Spring of 2006 will be used for the characterization of electric and chemical thruster performance as well as plume characterization. The system will include a Stokes rotary mechanical pump/positive displacement blower combination to provide a pumping speed of over 560 liters/sec at low vacuum ( $10^{-2}$  -  $10^{-3}$  Torr). For tests requiring higher vacuum at lower throughput, a 16-inch cryopump will provide an ultimate pressure in the low  $10^{-6}$  Torr range.

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.

Hardware fabrication is supported by two machine shops within the Mechanical Engineering Department. 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.

## **Controls and Mechatronics Lab (CML)**

The CML housed in HL248 has state-of-the-art data acquisition and control capabilities for experimental verification of intelligent control algorithms. Applications include, structural, structural-acoustic,

fluid-structure and mechatronics systems in aerospace or mechanical engineering.

Equipment include several dSPACE and two QUANSER Hardware-in-The-loop Board with WinCon 4.1 Real-Time Control Software. To validate real-time vibration control experiments the lab has a TMC active vibration isolation table, four ACX single-channel high voltage/low amps power amplifiers, one 2-channel Krohn-hite power amplifier, and one 6-channel rack mounted PCB power amplifier for piezoceramic patch actuation. For acceleration measurements CML has five PCB miniature (0.5g) shear ICP<sup>®</sup> accelerometers and PCB ICP<sup>®</sup> microphones for pressure measurements. For calibration and signal conditioning, CML has a Krohn-hite Low-Pass/High-Pass Butterworth/Bessel 4-Channel Filter, 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. In addition, CML has an Agilent 20Mhz Function/Arbitrary waveform generator and dedicated workstations for control design and implementation accessing Matlab's Real-Time Workshop, Optimization, Linear Matrix Inequalities and Robust Control toolboxes.

## **Hydrodynamics Laboratory**

This laboratory provides experimental facilities and instrumentation for characterization of liquid flow phenomena. A free surface water tunnel with a 2x2-foot test section and vertical water tank are available. These facilities allow for flow visualization and are supported by data acquisition systems and various flow measurement devices.

## **Dynamic Simulation Laboratory (DYSIM Lab)**

This is a general purpose PC laboratory that exposes large numbers of students to modern dynamic and geometric simulation techniques. Students use the DYSIM Lab to perform simulated experiments and observe demonstrations of course topics. The lab is equipped with 40 PCs that are connected through the computation network and direct links to other design process components.

## **Vibrations and Dynamics Laboratory**

This facility houses equipment to support educational, project and research activities in the area of vibrations and controls. This is also a teaching laboratory for the development of analytical and experimental skills in modern engineering measurement methods, based on electronic instrumentation and computer-based data acquisition systems.

## **Biomechanical Engineering Laboratory**

This laboratory provides experimental and computational facilities for research in the area of biomechanics and biofluids. Facilities include a hot wire anemometry system, PC-based computational facilities and ancillary equipment. The laboratory is also equipped with anatomical dissection facilities; kinematic data acquisition systems; instrumentation for measuring acceleration, velocity, force and pressure; and computer data acquisition systems. A MTS Mini Bionex testing machine is available to test materials in tension/compression and torsion.

## **Rehabilitation Engineering Laboratory**

This laboratory focuses on the development of assistive devices for persons with disabilities. The laboratory also conducts investigations involving prostheses and orthoses. The Assistive Technology Resource Center is associated with this laboratory.

## **Center for Holographic Studies and Laser Technology (CHSLT)**

CHSLT is used for both research and educational activities. The laboratory is equipped with several systems utilizing He-Ne, Arion, and Nd:TAG Lasers.

The lab is supported by a self-contained network of computers and peripheral facilities, as well as supporting instrumentation systems. The lasers, computers and supporting instrumentation are used in studies of fundamental phenomena governing high-energy-density interactions in thin film imaging, with powder metal materials, plastics, ceramics and composites, micromachining, underwater propagation, holography, displacement and strain measurement, vibrations, fracture mechan-



ics, mathematical modeling, numerical computations and applications to other problems of modern science, engineering and technology.

## Keck Design Center – the Design Studios

These laboratories provide a prototype facility consisting of a design studio and a prototype production facility linked by computational equipment, and 20-30 high-end workstations with software support for video-picture-within-the-monitor teleconferencing to provide two-way communication of audio, video and data between the design studios and off-campus sites. In the computationally equipped studio, students have clustered seating around multiple workstations, and can discuss and/or analyze with remote sponsors or others in real time as changes are made. Part files can be ported to rapid prototyping machines or lithography units within the Design Center and beyond.

## Other Facilities

The following laboratories, located in the Washburn Shops, are described in the Manufacturing Engineering and Materials Science and Engineering program descriptions:

- Metal Processing Laboratory
  - Advanced Casting Research Center (ACRC)
  - Center for Heat Treating Excellence (CHTE)
  - The Morris Boorky Powder Metallurgy Research Center (PMRC)
- Ceramic/Powder Processing Laboratory
- Mechanical Testing Laboratory
- Optical and Electron Metallography Laboratories
- Polymer Laboratory
- HAAS Center for Computer-Controlled Machining
- Robotics Laboratory
- Surface Metrology Laboratory
- Computer-Aided Manufacturing Laboratory

## 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.

**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

**Daniel Backman**, Research Professor, Sc.D., Massachusetts Institute of Technology, 1975; Materials modeling, solidification, and aerospace materials and processes.

**John J. Blandino**, Assistant 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, fractal analysis, mechanics of skiing, tribology, axiomatic design, materials science, computational modeling in surface metrology.

**Eben C. Cobb**, Visiting Assistant Professor; Ph.D., University of Connecticut, 1985; 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, 1993; Control of intelligent systems, control of fluid structure interactions, fault detection and accommodation of dynamical systems, acoustic and vibration control.

**Chrysanthe Demetry**, Associate Professor, Director of the Center for Educational Development and Assessment; Ph.D., Massachusetts Institute of Technology, 1993; Nanocrystalline materials and nanocomposites, materials processing, grain boundaries and interfaces in 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.

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

**Cosme Furlong-Vasquez**, Assistant Professor; Ph.D., WPI, 1999; MEMS and MOEMS, nanotechnology, mechatronics, laser applications, holography, computer modeling of dynamic systems

**Nikolaos A. Gatsonis**, Professor and Director, Aerospace Engineering Program; Ph.D. Massachusetts Institute of Technology, 1991; Development of numerical simulation methods and modeling of nonequilibrium, multi-component, multi-scale, gaseous and plasma flows; continuum/atomistic simulation of macro-, micro- and nano-scale fluid transport processes; development of plasma diagnostics and microfluidic devices; spacecraft propulsion and micro-propulsion; spacecraft/environment interactions.

**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 multi-agent systems, optimal control theory, and nonlinear dynamics and control.

**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.

**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.

**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.

**Yong-Mo Moon**, Assistant Professor; Ph.D., University of Michigan, 2000; Mechanisms and reconfigurable machinery design, design methodology, control, and mechanisms design.

**Robert L. Norton**, Professor; 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, chaos theory.

**Ryszard J. Pryputniewicz**, Professor; Ph.D., University of Connecticut, 1976; MEMS, 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**, 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.

**Richard D. Sisson, Jr.**, 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.

## Course Descriptions

All courses are 3 credits unless otherwise noted.

### 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.)

#### ME 613. Transport Phenomena

Conservation laws, with an emphasis on the similarities between the different mechanisms for the transport of heat, mass and momentum. Theory of molecular transport. Diffusion phenomena in stationary, flowing and unsteady processes. Mass diffusion in chemically reacting, multiphase and multicomponent systems. Computational techniques. Selected special topics and applications may include turbulent convective flows, combustion and materials processing.

## 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 of 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 532. Continuum Mechanics

Emphasis on the distinction between general principles that apply to all deforming materials and the specific constitutive assumptions that are made when modeling material behavior. The course includes a brief review of the necessary mathematics and then proceeds to the kinematics of deformable media, the concepts of stress and stress transformations, and the general balance laws. The remainder of the course deals with general constitutive theory and constitutive relations for selected materials that have relevance to structural, fluid dynamics, materials processing and materials handling.

### 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 631. Advanced Mechanics of Solids**

This course is a continuation of ME 531. Depending on the instructor, it will include a selection of the following topics: exact solutions for three-dimensional problems using vector potentials, Hertz contact solution, energy methods, elastic stability, an overview of plates and shells, and an introduction to plasticity and viscoelasticity theory.

### **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.)

### **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.)

### **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:

**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.

**Liquids** – 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; Ph.D., Northwestern University; Quantum information theory.

**N. A. Burnham**, Associate Professor; Ph.D., University of Colorado; Mechanical properties of nanostructures, instrumentation for nanomechanics.

**Declan DePaor**, Research Professor; Ph.D., National University of Ireland; Stress, strain, and kinematic analyses of rocks, crustal deformation on Earth and Mars, computer visualization in geology and geophysics, digital geological mapping and geoevaluation.

**R. Garcia**, Assistant Professor; Ph.D., Penn State University; Casimir forces, phase transitions, and wetting phenomena.

**S. N. Jaspersen**, Professor; Ph.D., Princeton University; Optical properties of solids, optical instruments.

**T. H. Keil**, Professor; Ph.D., University of Rochester; Solid state physics, mathematical physics, fluid mechanics.

**C. Koleci**, Assistant Professor; Ph.D., Brown University; Physics education.

**J. Norbury**, Research Professor; Ph.D., University of Idaho

**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.

**A. Zozulya**, Professor; Ph.D., Lebedev Physics Institute; Nonlinear optics, photorefractive materials, atom optics.

## 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)

Title and description of recently offered courses include:

- **PH 597A Topics in 21st Century Physics**
- **PH 597B Mathematical Methods of Physics**  
Vector calculus, special functions, calculus of variations, linear transformation theory, Green's functions, complex variables and integral equations.
- **PH 597C Careers in Physics**
- **PH 597D Group Theory**  
Theory of group representations; point groups and continuous groups of physical interest; applications to molecular vibrations, crystal properties, quantum mechanics and particle physics.

- **PH 597E Quantum Mechanics III**

Quantum theory of radiation and introduction to quantum field theory. (Prerequisite: PH 515)

- **PH 597F Quantum Theory of Solids**

Advanced topics in the quantum theory of solids. (Prerequisite: PH 533)

- **PH 597G Advanced Electrodynamics**

Classical electron theory, retarded potentials, radiation. (Prerequisite: PH 533)

- **PH 597H Thermodynamics**

Classical thermodynamics, equations of state, phase diagrams and transitions.

- **PH 597I Advanced Topics in Condensed Matter: Liquid Crystals**

Introduction to liquid crystals, phases and phase transitions, molecular models, applications.

- **PH 597J Complex Fluids I: Biophysical Chemistry**

- **PH 597K Liquids I: Molecular Dynamics of Simple Liquids**

- **PH 597L Quantum Semiconductor Heterostructures**

- **PH 597M Math Methods in Physics**

- **PH 597N Numerical Methods of Physics**

- **PH 597P Photonics**

Fiber optics, lasers, light emitting diodes, photodetectors, planar optical waveguides, fiber lasers and fiber amplifiers. (Prerequisite: B.Sc. degree in physics or equivalent.)

- **PH 597Q Qualifier Exam Prep**

- **PH 597R Interaction of Radiation and Matter**

Quantum theory of radiation, interacting systems, magnetic resonance, laser models and relaxation phenomena.

- **PH 597T Methods of Teaching Labs**

### 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.

### M. Sc. Thesis Research

(varies)

Each student will work under the supervision of a member of the department on an experimental or theoretical problem.

### 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 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 coursework selected from the following:

- SD 590 Special Topics in System Dynamics (credit as specified)
- MA 510/CS522 Numerical Methods (3 credit hours)

- MA 514 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 online 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 Applied 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 70.

### 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 CGSR.

### 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

**Khalid Saeed**, Professor and Department Head; Ph.D., Massachusetts Institute of Technology, 1981; sustainable economic development, system dynamics; organizational development, political economy; saeed@wpi.edu

**James K. Doyle**, Associate Professor; 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

**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.

**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

## 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

**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 managers) and the system dynamics standard method - a sequence of steps leading from a fuzzy "issue area" through increasing clarity and ultimately to solution recommendations. The course provides clear project pacing and lots of support from the instructors and fellow students. It is recommend that students take SD 552 Real World System Dynamics toward the end of their system dynamics coursework as it provides a natural transition from coursework to system dynamics practice. Prerequisites: SD 550 System Dynamics Foundation: Managing Complexity and SD 551 Modeling and Experimental Analysis of Complex Problems

### SD 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.

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# 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..... 508-831-6088

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..... 508-831-5067

Administrative Services ..... 508-831-5150

Admissions (graduate)..... 508-831-5301

Admissions  
(undergraduate) ..... 508-831-5286

Advanced Distance  
Learning Network..... 508-831-5220

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..... 508-831-5010

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 Studies  
and Enrollment..... 508-831-5301

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 ..... 508-831-5610

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

Registrars 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..... 508-831-5744

Sports Information..... 508-831-5328

Student Activities ..... 508-831-5291

Student Development &  
Counseling Center ..... 508-831-5540

Student Affairs &  
Campus Life ..... 508-831-5060

Student Night Assistance  
Patrol (SNAP)..... 508-831-5433

Summer Programs..... 508-831-5999

Telecommunications ..... 508-831-5210

University Advancement .... 508-831-5612

Web Development ..... 508-831-5963

Women's Programs..... 508-831-5819

## **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 Department of Management 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.

### To WPI's MetroWest Campus

at the Massachusetts Technology Collaborative

75 North Drive

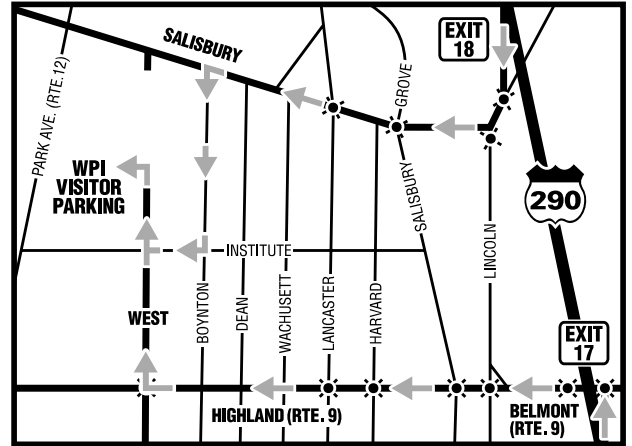
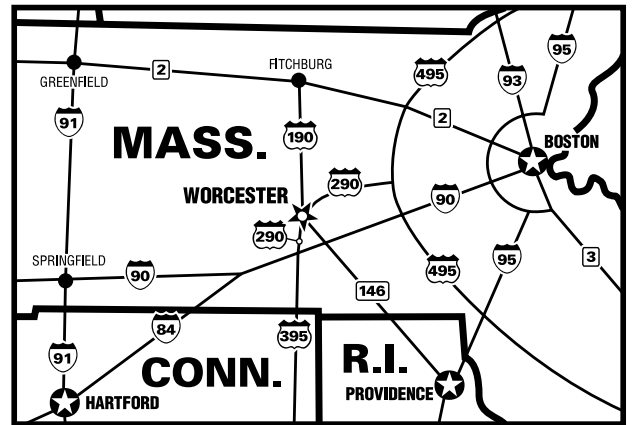
Westborough, MA 01581

Phone: 508-870-0312

WPI offers graduate courses and extended education seminars in Westborough, Mass. The UMass I-495 Center for Professional Education is located in the Karl Weiss Education and Conference Center on the campus of the Massachusetts Technology Collaborative. The Center is highly accessible with convenient parking and close proximity to I-495 and the Massachusetts Turnpike. WPI courses meet in Room 109 of the Weiss Center.

**From the north or south:** Take I-495 to Exit 23B (Route 9, westbound). Proceed west on Route 9 for 3.3 miles to its intersection with Route 135. Turn right onto 135 west and follow it 0.4 mile to North Drive, the Massachusetts Technology Collaborative entrance on the right.

**From the east or west:** Take the Massachusetts Turnpike and exit at Exit 11A; take I-495 north, take Exit 23B (Route 9, westbound). Proceed west on Route 9 for 3.3 miles to its intersection with Route 135. Turn right onto 135 west and follow it 0.4 mile to North Drive, the Massachusetts Technology Collaborative entrance on the right.



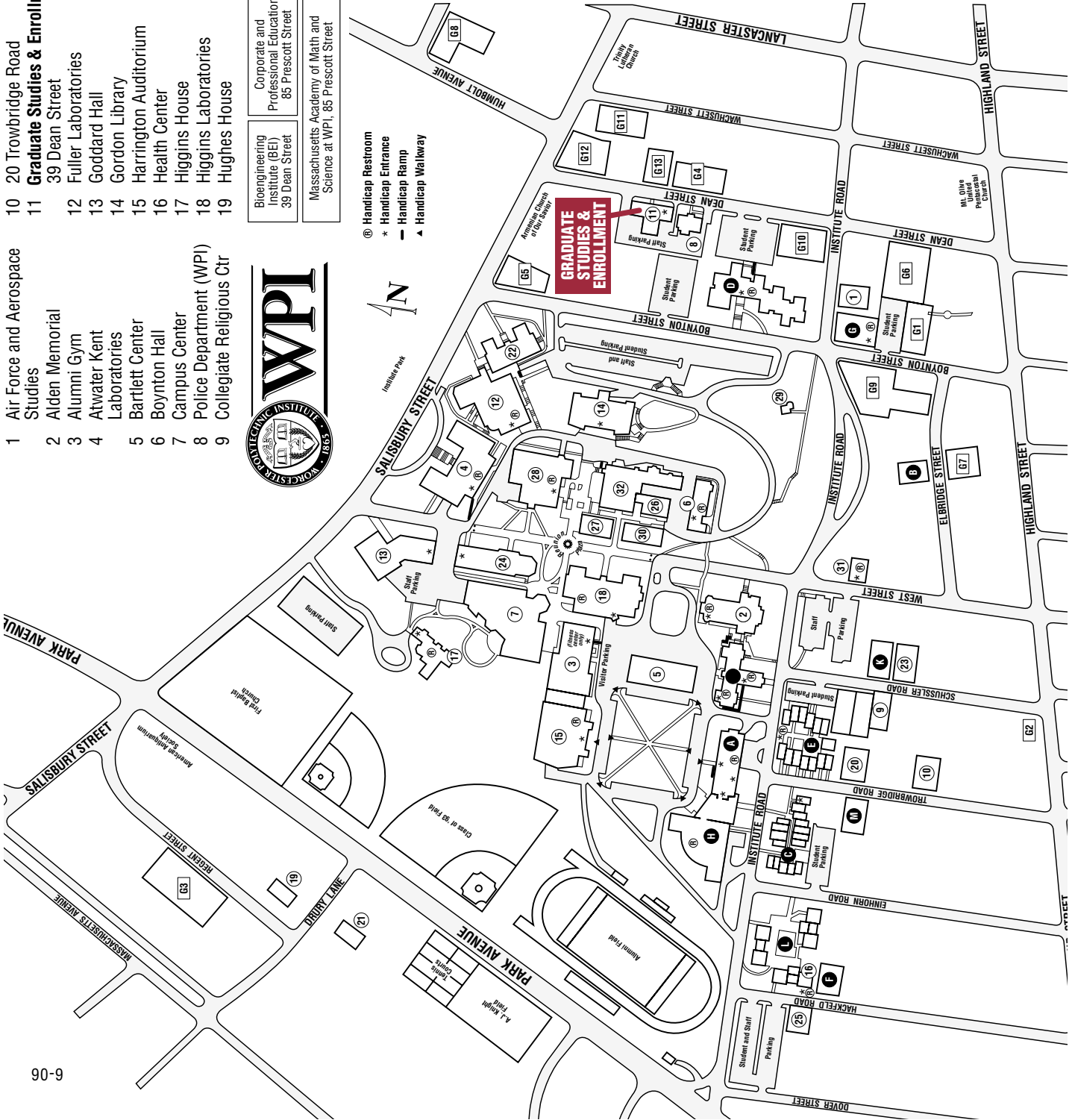
- 1 Air Force and Aerospace Studies
- 2 Alden Memorial Alumni Gym
- 3 Alumni Gym
- 4 Atwater Kent Laboratories
- 5 Bartlett Center
- 6 Boynton Hall
- 7 Campus Center
- 8 Police Department (WPI)
- 9 Collegiate Religious Ctr
- 10 20 Trowbridge Road
- 11 **Graduate Studies & Enrollment**
- 12 Fuller Laboratories
- 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

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- 31 Student Development and Counseling Center
- 32 Washburn Shops and Stoddard Laboratories

Bioengineering Institute (BEI) 39 Dean Street	Corporate and Professional Education 85 Prescott Street
Massachusetts Academy of Math and Science at WPI, 85 Prescott Street	



- Ⓞ Handicap Restroom
- \* Handicap Entrance
- Handicap Ramp
- ▲ Handicap Walkway



- 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

- Greek Houses**
- G1 Alpha Chi Rho
  - G2 Alpha Gamma Delta
  - G3 Alpha Tau Omega
  - G4 Lambda Chi Alpha
  - G5 Phi Gamma Delta
  - G6 Phi Sigma Kappa
  - G7 Phi Sigma Sigma
  - G8 Sigma Alpha Epsilon
  - G9 Sigma Phi Epsilon
  - G10 Sigma Pi
  - G11 Tau Kappa Epsilon
  - G12 Theta Chi
  - G13 Zeta Psi

## **Graduate Studies & Enrollment**

**Worcester Polytechnic Institute**

100 Institute Road

Worcester, MA 01609-2280