The Department of Applied Mathematics and Statistics is devoted to the study and development of mathematical disciplines especially oriented to the complex problems of modern society. A broad undergraduate and graduate curriculum emphasizes several branches of applied mathematics: Probability, the mathematical representation and modeling of uncertainty; Statistics, the analysis and interpretation of data; Operations Research, the design, analysis, and improvement of actual operations and processes; Optimization, the determination of best or optimal decisions; Discrete Mathematics, the study of finite structures, arrangements, and relations; Scientific Computation, which includes all aspects of numerical computing in support of the sciences; and Financial Mathematics, the modeling and analysis of financial markets.

Probability and Statistics is treated in the curriculum as a single general area, dealing in a unified way with theory and methodology for probabilistic representation of chance phenomena, applications of stochastic modeling to physical and social sciences, formulation of statistical models, fitting of statistical models to data, and interpretation of data. Operations Research and Optimization represents a second general area, dealing in unified fashion with the application of optimization theory, mathematical programming, computer modeling, stochastic modeling, and game theory to planning and policy problems such as scheduling, allocation of resources, and facility location. Discrete Mathematics includes the traditional themes of graph theory and combinatorics, as well as newer topics arising from modern technological and theoretical developments. The fourth general area, Computational and Applied Mathematics, covers topics pertaining to computing, numerical analysis, advanced matrix analysis, and mathematical modeling. Financial Mathematics addresses applications by making use of applied mathematics techniques and models from many of the above-mentioned areas.

In its fundamental role of representing applied mathematics at Johns Hopkins University, the Department of Applied Mathematics and Statistics is complemented by the Department of Mathematics, with its differing emphasis. Located in the School of Engineering, the Department of Applied Mathematics and Statistics fulfills a special integrative role, stemming in part from the affinity of engineers for applied mathematics and in part from the increasing need for interaction between science and engineering. The mathematical sciences, especially the mathematics of modeling, provide a common language and tools through which engineers can develop closer alliances and cooperation with other scientists.

The department's degree programs include foundational and introductory course work drawing from all areas of the curriculum, along with specialized course work in areas such as probability, statistics, operations research, and optimization. Students, in consultation with their advisors, may develop challenging individual programs. The department emphasizes mathematical reasoning, mathematical modeling, abstraction from the particular, and innovative application all in a problem-oriented setting. The aim is to prepare graduates for professional careers in the mathematical sciences and related areas, in academic institutions as well as in governmental, industrial, and research organizations.

The undergraduate major in applied mathematics and statistics leads to the B.A. and B.S. degrees. The graduate program leads to the M.A., M.S.E., and Ph.D. degrees. In addition, under a combined bachelor’s/master’s program, exceptionally able undergraduates may be admitted early to simultaneous graduate work.

Facilities
The department is located in Whitehead Hall. Office space and liberal access to computing facilities are provided to resident graduate students. A Reading/Commons Room provides the opportunity for informal discussions among faculty and graduate students. The university’s Milton S. Eisenhower Library maintains an excellent collection of literature in the mathematical sciences, including all of the important current journals.

Undergraduate Programs
The undergraduate major in applied mathematics and statistics may serve as preparation for employment as an applied mathematician, for graduate study in applied mathematics or related areas, or as a general quantitative training for a career in business, medicine, or other fields. An undergraduate major in applied mathematics and statistics takes an individually tailored program of courses within the department and in the Department of Mathematics (calculus, and perhaps further courses such as differential equations, analysis, complex variables, topology, and modern algebra) and electives in science and engineering. By suitable choice of electives, heavy concentration in a specific field of engineering is possible.

In order to develop a sound program suited to individual needs and interests, the student should consult regularly with the faculty advisor. Additional advisory information, including information about the areas of focus described below, may be obtained from the department office.

With the advice and consent of the faculty advisor, each student constructs an individualized program meeting the requirements below. A written copy of the program should be on file with the faculty advisor, with whom it can be revised and updated from time to time.

Bachelor's Degrees
Departmental majors can earn either the B.A. or the B.S. degree by meeting the general university requirements and the general requirements of the School of Engineering (see Requirements for a Bachelor's Degree, Writing Requirement, in this catalog), and the departmental requirements.

All courses used to meet the following departmental requirements must be taken for a letter grade and passed with grade of C- or higher.

1. Calculus I, II, and III

<table>
<thead>
<tr>
<th>Course</th>
<th>Description</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>AS.110.106 &amp; AS.110.107</td>
<td>Calculus I (Biology and Social Sciences) and Calculus II (For Biological and Social Science)</td>
<td>4-8</td>
</tr>
<tr>
<td>or AS.110.108 &amp; AS.110.109</td>
<td>Calculus I and Calculus II (For Physical Sciences and Engineering)</td>
<td></td>
</tr>
<tr>
<td>or AS.110.113</td>
<td>Honors Single Variable Calculus</td>
<td></td>
</tr>
<tr>
<td>AS.110.202</td>
<td>Calculus III</td>
<td>4</td>
</tr>
<tr>
<td>or AS.110.211</td>
<td>Honors Multivariable Calculus</td>
<td></td>
</tr>
</tbody>
</table>

2. Linear Algebra and Differential Equations
Two courses in linear algebra and differential equations. These two courses must, collectively, touch both areas. There are two ways to meet this two-course requirement:

Option A
Choose one of the following for Linear Algebra:

- AS.110.201 Linear Algebra
- or AS.110.212 Honors Linear Algebra

Choose one of the following for Differential Equations:

- AS.110.302 Differential Equations and Applications
- or AS.110.417 Partial Differential Equations
- or EN.553.281 Scientific Computing: Differential Equations
- or EN.553.388 Scientific Computing: Differential Equations in Vector Spaces
- or EN.553.391 Dynamical Systems

Option B
EN.553.291 Linear Algebra and Differential Equations

Plus an additional course in linear algebra or differential equations chosen from among the following:

- EN.553.385 Scientific Computing: Linear Algebra
- or EN.553.386 Scientific Computing: Differential Equations
- or EN.553.388 Scientific Computing: Differential Equations in Vector Spaces
- or EN.553.391 Dynamical Systems
- or EN.553.792 Matrix Analysis and Linear Algebra
- or AS.110.417 Partial Differential Equations


Choose one of the following (or one of the courses approved to meet the Master’s/PhD Computing Requirement):

- AS.250.205 Introduction to Computing
- or EN.500.200 Computing for Engineers and Scientists
- or EN.510.202 Computation and Programming for Materials Scientists and Engineers
- or EN.530.371 Quantitative Applications in Mechanical Engineering
- or EN.540.305 Modeling and Statistical Analysis of Data for Chemical and Biomolecular Engineers
- or EN.553.281 Introduction to Mathematical Programming
- or EN.553.383 Scientific Computing with Python
- or EN.553.385 Scientific Computing: Linear Algebra
- or EN.553.386 Scientific Computing: Differential Equations
- or EN.553.388 Scientific Computing: Differential Equations in Vector Spaces
- or EN.553.400 Mathematical Modeling and Consulting
- or EN.553.413 Applied Statistics and Data Analysis
- or EN.553.433 Monte Carlo Methods
- or EN.553.436 Data Mining
- or EN.553.443 Financial Computing in C++
- or EN.553.450 Computational Molecular Medicine
- or EN.553.487 Numerical Methods for Financial Mathematics
- or EN.553.488 Financial Computing I
- or EN.553.493 Mathematical Image Analysis
- or EN.560.220 Civil Engineering Programming
- or EN.570.210 Computation/Math Modeling
- or EN.580.200 Introduction to Scientific Computing in BME using Python, Matlab, and R

or EN.580.223 Models and Simulations
or EN.601.475 Machine Learning
or EN.601.482 Machine Learning: Deep Learning

4. Discrete Mathematics
Choose one of the following:

- EN.553.171 Discrete Mathematics
- or EN.553.172 Honors Discrete Mathematics
- or EN.553.371 Cryptology and Coding
- or EN.553.471 Combinatorial Analysis
- or EN.553.472 Graph Theory

5. Probability and Statistics

EN.553.420 Introduction to Probability
EN.553.430 Introduction to Statistics

6. Optimization

EN.553.361 Introduction to Optimization

7. Completion of an area of Focus, chosen from the list below.

Two additional courses are to be taken in the area of focus, distinct from those used to satisfy requirements 5 and 6.

8. Courses coded Quantitative Studies totaling 40 credits of which at least 18 credits must be in courses numbered 300 or higher. (Courses used to meet the requirements above may be counted toward this total.)

9. For the B.S. degree, at least 12 credits coded Natural Sciences Laboratory courses that accompany Natural Science courses may be used in reaching this total. (Courses used to meet the requirements above may be counted toward this total.)

Area of Focus

Two additional courses are to be taken in the area of focus.

Probability and Stochastic Processes
Choose two of the following:

- AS.110.405 Real Analysis I
- EN.553.426 Introduction to Stochastic Processes
- EN.553.427 Stochastic Processes and Applications to Finance
- EN.553.433 Monte Carlo Methods
- EN.553.492 Mathematical Biology

Statistics and Statistical Learning
Choose two of the following:

- EN.553.400 Mathematical Modeling and Consulting
- EN.553.413 Applied Statistics and Data Analysis
- EN.553.414 Applied Statistics and Data Analysis II
- EN.553.416 Introduction to Statistical Learning, Data Analysis and Signal Processing
- EN.553.417 Mathematical Modeling: Statistical Learning
- EN.553.433 Monte Carlo Methods
- EN.553.436 Data Mining
- EN.553.439 Time Series Analysis
- EN.553.450 Computational Molecular Medicine

Optimization and Operations Research
Choose two of the following:

- EN.553.362 Introduction to Optimization II
- EN.553.400 Mathematical Modeling and Consulting
- EN.553.453 Mathematical Game Theory
### Discrete Mathematics

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN.553.463</td>
<td>Network Models in Operations Research</td>
</tr>
<tr>
<td>EN.553.465</td>
<td>Introduction to Convexity</td>
</tr>
</tbody>
</table>

### Scientific Computing

Choose two of the following: 7-8

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN.553.383</td>
<td>Scientific Computing with Python</td>
</tr>
<tr>
<td>EN.553.385</td>
<td>Scientific Computing: Linear Algebra</td>
</tr>
<tr>
<td>EN.553.386</td>
<td>Scientific Computing: Differential Equations</td>
</tr>
<tr>
<td>EN.553.388</td>
<td>Scientific Computing: Differential Equations in Vector Spaces</td>
</tr>
<tr>
<td>EN.553.433</td>
<td>Monte Carlo Methods</td>
</tr>
</tbody>
</table>

* Neither the pair of EN.553.385-EN.553.386 nor EN.553.386-EN.553.388 allowed in fulfillment of the area of focus.

### Minor in Applied Mathematics and Statistics

The minor in applied mathematics and statistics should be attractive to students majoring in a variety of disciplines, in both the School of Engineering and the School of Arts and Sciences. The minor provides formal recognition of the depth and strength of a student’s quantitative knowledge beyond the minimal requirements of his/her major.

The requirements of the minor in applied mathematics and statistics are the following:

- Completion of an approved program of study containing at least 18 credits in courses coded Quantitative Studies. The first two courses in calculus (AS.110.106 Calculus I (Biological and Social Sciences)-AS.110.107 Calculus II (For Biological and Social Science) or AS.110.108 Calculus I-AS.110.109 Calculus II (For Physical Sciences and Engineering) or their equivalents) may not be used to fulfill this requirement.

- Among the courses comprising the 18 Q credits, there must be:
  - at least four courses in the Department of Applied Mathematics and Statistics (each of these must be a 3- or 4-credit course);
  - at least three 3- or 4-credit courses coded Q at the 300-level or above, of which at least two must be in the Department of Applied Mathematics and Statistics; and
  - one of the courses approved to meet the AMS Master’s/PhD Computing Requirement (http://engineering.jhu.edu/ams/courses-approved-meet-ams-mastersph-d-computing-requirement).

### Honors

The Department of Applied Mathematics and Statistics awards departmental honors based on a number of factors, including performance in coursework, research experiences, teaching, and service. If a student completes a senior thesis (EN.553.501 Senior Thesis) and also earns a GPA of 3.5 or higher in Applied Mathematics and Statistics courses, then the student will automatically be awarded departmental honors.

**Requirements 1–9 together constitute a minimal core program, allowing maximum flexibility in planning degree programs. Students often are able to complete a second major during a four-year program or to proceed to the department’s combined bachelor’s/master’s degree program.**

It is highly recommended that students develop a coherent program of study (see below) or at least take additional departmental courses, in order to establish a broad foundation for a career as an applied mathematician. Of particular importance are additional courses in optimization (EN.553.362 Introduction to Optimization II), stochastic processes (EN.553.426 Introduction to Stochastic Processes), statistics (EN.553.413 Applied Statistics and Data Analysis), dynamical systems (EN.553.391 Dynamical Systems), mathematical modeling and consulting (EN.553.400 Mathematical Modeling and Consulting), scientific computing (EN.553.385 Scientific Computing: Linear Algebra, EN.553.386 Scientific Computing: Differential Equations), and investment science (EN.553.442 Investment Science). Students planning to continue to graduate school in an applied mathematics program are encouraged to consider taking one or more graduate-level courses in probability (EN.553.720 Probability Theory I, EN.553.721 Probability Theory II), statistics (EN.553.730 Statistical Theory, EN.553.731 Statistical Theory II), optimization (EN.553.761 Nonlinear Optimization I, EN.553.762 Nonlinear Optimization II), combinatorics (EN.553.671 Combinatorial Analysis), graph theory (EN.553.672 Graph Theory), numerical analysis (EN.553.781 Numerical Analysis), or matrix analysis (EN.553.792 Matrix Analysis and Linear Algebra).
or EN.553.487 Numerical Methods for Financial Mathematics
or EN.553.486 Financial Computing I
or EN.553.493 Mathematical Image Analysis
or EN.560.220 Civil Engineering Programming
or EN.570.210 Computation/Math Modeling
or EN.580.200 Introduction to Scientific Computing in BME using Python, Matlab, and R
or EN.580.223 Models and Simulations
or EN.601.476 Machine Learning
or EN.601.482 Machine Learning: Deep Learning

• All courses used to meet AMS departmental minor requirements must be taken for a letter grade and passed with grade of C- or higher.
• Students may not count all 3 courses, EN.553.310 Probability & Statistics/EN.553.311 Probability and Statistics for the Biological Sciences and Engineering, EN.553.420 Introduction to Probability, and EN.553.430 Introduction to Statistics toward minor requirements.
• A student wishing to complete a minor in applied mathematics and statistics may obtain more information from the Applied Mathematics and Statistics Department office.

Graduate Programs

A wide variety of advanced courses, seminars, and research opportunities is available in the Department of Applied Mathematics and Statistics. In addition to graduate programs in probability, statistics, operations research, optimization, discrete mathematics, scientific computation, and financial mathematics, advanced study is possible in interdisciplinary topics in cooperation with other departments, particularly the departments of Biostatistics, Computer Science, Economics, Environmental Health and Engineering, Health Services Administration, Mathematics, and Sociology. A graduate student in the Department of Applied Mathematics and Statistics may thus develop a program that suits his/her individual interests and objectives.

Various elements of the graduate program are summarized below. Further information is available from the department office.

Admission

To be admitted to an advanced degree program in the department, an applicant must show that he/she has the basic intellectual capacity and has acquired the skills necessary to complete the program successfully within a reasonable period of time. A faculty committee evaluates each applicant’s credentials; there are no rigid requirements.

Prospective applicants should submit transcripts of previous academic work, letters of recommendation from persons qualified to evaluate the applicant’s academic performance and potential for graduate study, a statement of purpose describing anticipated professional goals, and Graduate Record Examination (GRE) scores. Foreign students must submit scores from the Test of English as a Foreign Language (TOEFL) or International English Language Testing System (IELTS).

Most applicants have undergraduate majors in quantitative fields such as mathematics, statistics, engineering, or a field in the physical sciences, but any major is permitted. Regardless of the major, completion of a program in undergraduate mathematics at least through advanced calculus and linear algebra is essential to begin the normal graduate program.

Requirements for the Master’s Degree in Applied Mathematics and Statistics

Students may elect to work toward either the master of arts (M.A.) degree or the master of science in engineering (M.S.E.) degree in applied mathematics and statistics. All master’s degrees in applied mathematics and statistics ordinarily require a minimum of two semesters of registration as a full-time resident graduate student.

To obtain departmental certification for the master’s degree in Applied Mathematics and Statistics, the student must:

1. Complete satisfactorily at least eight one-semester courses of graduate work in a coherent program approved by the faculty advisor. All 600-level and 700-level courses (with the exception of seminar and research courses), are satisfactory for this requirement. Certain courses in other departments are also acceptable, and must be approved in advance. At most 3 courses outside the department may be counted toward the Master’s degree requirements. WSE courses listed as 1- or 2-credit courses count only as one-half course. Approved KSAS graduate courses count as one-half course if the number of meeting hours per week is 1 or 2 and count as a full course otherwise.

2. Meet either of the following options:
   • (a) submit an acceptable research report based on an approved project; or
   • (b) complete satisfactorily two additional one-semester graduate courses, as approved by the faculty advisor.

3. Satisfy the computing requirement by receiving a grade of B- or better in one of the following courses:
   - EN.553.600 Mathematical Modeling and Consulting
   - EN.553.613 Applied Statistics and Data Analysis
   - EN.553.633 Monte Carlo Methods
   - EN.553.636 Data Mining
   - EN.553.650 Computational Molecular Medicine
   - EN.553.688 Financial Computing I
   - EN.553.693 Mathematical Image Analysis
   - EN.553.732 Bayesian Statistics
   - EN.553.744 Graphical Models
   - EN.553.753 Commodities and Commodity Markets
   - EN.553.761 Nonlinear Optimization I
   - EN.553.762 Nonlinear Optimization II
   - EN.553.763 Stochastic Search & Optimization
   - EN.553.765 Convex Optimization
   - EN.553.780 Shape and Differential Geometry
   - EN.553.781 Numerical Analysis
   - EN.601.675 Machine Learning
   - EN.601.682 Machine Learning: Deep Learning

4. Complete an area of focus by taking three courses in one of the following areas. A list of courses that can be counted toward each area of focus will be maintained and updated every year. Some courses from other departments can be eligible to count toward area of focus. They can be used within the three-course limit specified in point 1, above. This list of courses is based on recent offerings. Not all classes are available every year and substitute classes may be accepted if approved by the advisor and the Academic Affairs Committee.

Probability Theory
EN.553.626  Introduction to Stochastic Processes  4  
EN.553.627  Stochastic Processes and Applications to Finance  4  
EN.553.628  Stochastic Processes and Applications to Finance II  4  
EN.553.633  Monte Carlo Methods  4  
EN.553.720  Probability Theory I  4  
EN.553.721  Probability Theory II  4  
EN.553.722  Introduction to Stochastic Calculus  3  
EN.553.763  Stochastic Search & Optimization  3  
EN.553.764  Modeling, Simulation, and Monte Carlo  3  

Statistics and Statistical Learning  
EN.553.613  Applied Statistics and Data Analysis  4  
EN.553.614  Applied Statistics and Data Analysis II  3  
EN.553.650  Computational Molecular Medicine  4  
EN.553.730  Statistical Theory  4  
EN.553.731  Statistical Theory II  3  
EN.553.732  Bayesian Statistics  3  
EN.553.733  Advanced Topics in Bayesian Statistics  3  
EN.553.737  Distribution-free statistics and Resampling Methods  3  
EN.553.740  Machine Learning  3  
EN.553.782  Statistical Uncertainty Quantification  3  

Optimization and Operations Research  
EN.553.600  Mathematical Modeling and Consulting  4  
EN.553.661  Optimization in Finance  4  
EN.553.653  Mathematical Game Theory  4  
EN.553.663  Network Models in Operations Research  4  
EN.553.665  Introduction to Convexity  4  
EN.553.761  Nonlinear Optimization I  3  
EN.553.762  Nonlinear Optimization II  3  
EN.553.763  Stochastic Search & Optimization  3  
EN.553.765  Convex Optimization  3  
EN.553.766  Combinatorial Optimization  3  
EN.553.797  Introduction to Control Theory and Optimal Control  3  

Computational and Applied Mathematics  
EN.553.688  Financial Computing I  3  
EN.553.692  Mathematical Biology  3  
EN.553.693  Mathematical Image Analysis  3  
EN.553.780  Shape and Differential Geometry  3  
EN.553.781  Numerical Analysis  4  
EN.553.784  Mathematical Foundations of Computational Anatomy  3  
EN.553.792  Matrix Analysis and Linear Algebra  4  
EN.553.793  Turbulence Theory  3  
EN.553.795  Advanced Parameterization in Science and Engineering  3  

Discrete Mathematics *  
At least one of:  
EN.553.671  Combinatorial Analysis  4  
or EN.553.672 Graph Theory  
or EN.553.766 Combinatorial Optimization  

Additional options:  
EN.601.631  Theory of Computation  3  
EN.601.633  Intro Algorithms  3  
EN.601.634  Randomized and Big Data Algorithms  3  
EN.601.635  Approximation Algorithms  3  

* The Discrete Mathematics area of focus requires a minimum of one Applied Mathematics and Statistics course (listed in the first section), but the other two courses may include other listed Applied Mathematics and Statistics offerings or the listed Computer Science offerings. The Computer Science courses can be used within the three-course limit specified in point 1, above.

5. Complete training on the responsible and ethical conduct of research, if applicable. Please see WSE Policy on the Responsible Conduct of Research.

6. Complete training on academic ethics.

An overall GPA of 3.0 must be maintained in courses used to meet the program requirements. At most two course grades of C or C+ are allowed to be used and the rest of the course grades must be B- or better.

Each candidate for the master’s degree must submit to the department for approval a written program stating how they plan to meet their degree requirements. This should be done early in the first semester of residence.

Doctoral students in other departments may concurrently undertake a master’s program in Applied Mathematics and Statistics with the permission of the AMS department through an application review. Application information is available in the department office.

Requirements for the Master’s Degree in Financial Mathematics  
The department offers an M.S.E. degree in Financial Mathematics. The structure of this program is summarized below. More detailed information about this program may be found on the department’s website.

Full-time students in this program are expected to attend courses for three semesters beginning in the fall semester, a summer internship after the spring semester of their first year, and return for a second fall semester.

For departmental certification for this degree, the student must complete the following courses or approved substitute courses with program approval pursuing either the Legacy Track or Area of Focus Track:

Area of Focus Track  
Core financial mathematics requirements (2 courses)  
EN.553.644  Introduction to Financial Derivatives  4  
EN.553.645  Interest Rate and Credit Derivatives  4  

Core applied mathematics requirements (3 courses)  
EN.553.613  Applied Statistics and Data Analysis  4  
EN.553.627  Stochastic Processes and Applications to Finance  4  
EN.553.639  Time Series Analysis  3  

Electives *  
7 elective courses:  
One in Applied Mathematics and Statistics  4  

or EN.553.672 Graph Theory  
or EN.553.766 Combinatorial Optimization  

or EN.553.688 Combinatorial Optimization
The progress of students is evaluated at the study and dissertation research is based upon favorable evaluation of background, and affords a close view of the doctoral research process—a spectrum of topics, provides an opportunity to fill gaps in his or her background, and affords a close view of the doctoral research process.

The introductory phase of graduate study acquaints the student with can work at the current frontiers of their chosen specialized disciplines. Requirements for this program consist of those for the bachelor’s and master’s programs.

The requirements for this program consist of those for the bachelor’s and master’s programs. Highly motivated and exceptionally well-qualified undergraduates may apply for admission to the combined bachelor’s/master’s program in applied mathematics and statistics. Interested students should apply no later than fall semester of their senior year.

The requirements for this program consist of those for the bachelor’s and master’s programs.

Requirements for the Ph.D. Degree

The objective of the department’s Ph.D. program is to produce graduates who are broadly educated in applied mathematics and statistics and who can work at the current frontiers of their chosen specialized disciplines. The introductory phase of graduate study acquaints the student with a spectrum of topics, provides an opportunity to fill gaps in his or her background, and affords a close view of the doctoral research process and of potential research areas and advisors. Continuation to advanced study and dissertation research is based upon favorable evaluation of preparedness and potential. The progress of students is evaluated at the end of every semester. The culmination of the program is the doctoral dissertation, representing an original and significant contribution to knowledge in applied mathematics.

In addition to fulfilling the university requirement of a minimum of two consecutive semesters of registration as a full-time resident graduate student, the student must accomplish the following to obtain departmental certification for the Ph.D.:

- Pass the Introductory Examination, normally offered immediately before each semester.
- Pass the Ph.D. Candidacy Examination. This oral examination is normally taken in the third year of residency. The scope of the exam will be governed by a syllabus prepared by the student with the help of the student’s mentor or advisor.
- Pass the Graduate Board Oral Examination, normally taken in the third year of residence.
- Acquire teaching experience under the supervision of the faculty.
- Complete at least 12 one-semester courses of graduate work in a coherent program approved by the faculty advisor.
- Demonstrate a working knowledge of the utilization of computers in applied mathematics and statistics.
- Complete a program of original research and its clear exposition in a written dissertation. The dissertation must be approved by at least two faculty readers and be certified by them to be a significant contribution to knowledge and worthy of publication in scholarly journals. The candidate defends the dissertation in a public examination held under the auspices of the department.

Additional details on these items may be found on the department’s website.

Course Program

The most common way for students to gain the knowledge and skills to succeed in the Ph.D. program is through course work. In consultation with his or her advisor, each student will develop a program of proposed course work. The relevant courses for the Ph.D. are of three types: basic graduate-level courses, additional specialized courses appropriate to the student’s field of research, and an elective one year course selected to broaden the student in applied mathematics. To promote a well-rounded education and record, all full-time graduate students are expected to enroll in an appropriate number of courses for their stage in the program. Students are required to enroll in and attend EN.553.801 Department Seminar, the Applied Mathematics and Statistics Department Seminar, every semester. Grades of B- or better (or equivalent level of performance in pass/fail courses) are expected of all department Ph.D. graduate students in their course work.

Basic Courses

All students are encouraged to master basic material in:

- probability (EN.553.720), statistics (EN.553.730), and stochastic processes (EN.553.626);
- optimization (EN.553.761);
- numerical and matrix analysis (EN.553.781, EN.553.792); and
- discrete mathematics (EN.553.671, EN.553.672).

Normally, a student will have completed at least eight basic courses by the end of the fourth semester of residence.

- Two courses in Financial Mathematics 4
- Four additional courses from the approved electives listing or with prior program approval 4

Financial Mathematics Masters Seminar

Computing requirement (includes the Financial Computing Workshop)

Communication skills requirement (includes the Communication Skills Practicum)

Summer Internship

Legacy Track

Core financial mathematics requirements (4 courses)

EN.553.642 Investment Science 4
EN.553.644 Introduction to Financial Derivatives 4
EN.553.645 Interest Rate and Credit Derivatives 4

Core applied mathematics requirements (5 courses)

EN.553.627 Stochastic Processes and Applications to Finance 4
EN.553.633 Monte Carlo Methods 4
EN.553.613 Applied Statistics and Data Analysis 4
EN.553.639 Time Series Analysis 3
EN.553.661 Optimization in Finance 4

Electives *

3 elective courses:

One in Applied Mathematics and Statistics 4
One course in Financial Mathematics 4
One additional course with prior program approval 4

Financial Mathematics Masters Seminar

Computing requirement (includes the Financial Computing Workshop)

Communication skills requirement (includes the Communication Skills Practicum)

Summer Internship

For courses used toward the degree, all grades must be C or higher, at most two grades can be below a B-, and the overall average grade point average in these courses must be at least 3.0.

* Please see department website for approved electives.

Requirements for the Bachelor’s/Master’s Program

Highly motivated and exceptionally well-qualified undergraduates may apply for admission to the combined bachelor’s/master’s program in applied mathematics and statistics. Interested students should apply no later than fall semester of their senior year.

The requirements for this program consist of those for the bachelor’s and master’s programs.
Specialized Courses
Each student takes advanced courses appropriate to the proposed area of dissertation research, with the approval of the research advisor.

Elective Courses
Students are encouraged to take additional elective course work, either covering one area in depth or covering two areas. Typical areas in other departments are biology, econometrics, mathematical economics, mathematical ecology, computational geometry, systems theory, health systems, mathematics, facility location, psychometrics, and physics. These courses may complement or supplement the student's previous experience, but if a student has no previous experience in an area some elementary course work may be necessary as a prerequisite to acceptable graduate level courses.

Financial Assistance
A limited number of teaching and research assistantships providing full tuition and a competitive academic year stipend are available to qualified full-time Ph.D. candidates. Furthermore, the following special fellowships are awarded:

- The Rufus P. Isaacs Fellowship, named in honor of a late member of the faculty acclaimed for his contributions to operations research.
- The Charles and Catherine Counselman Fellowship, generously endowed by Hopkins alumnus Charles Counselman.

In addition, summer employment opportunities are often available within the university and in the Baltimore-Washington corridor.

Faculty
Chair
E. Laurent Younes
Professor: mathematical imaging, shape theory and applied differential geometry, computational probability, statistics.

Vice Dean for Graduate Education
Edward R. Scheinerman
Professor: discrete mathematics, graph theory, social networks, random methods, partially ordered sets.

Director of Graduate Studies
Daniel Q. Naiman
Professor, Director of Financial Mathematics Master’s Program: statistics, computational probability, bioinformatics.

Director of Undergraduate Studies
Donniell E. Fishkind
Associate Research Professor: combinatorics, graph theory, matrix analysis.

Associate Director of Undergraduate Studies
James A. Fill
Professor: probability, stochastic processes, random structures, and algorithms.

Executive Director of Financial Mathematics Master’s Program
David Audley
Senior Lecturer: financial mathematics, term structure models, fixed income derivatives, and quantitative portfolio strategies.

Professors
William J. Cook
Professor: combinatorial optimization, integer programming, operations research, large-scale computing.
Gregory L. Eyink
Professor: mathematical physics, fluid mechanics, turbulence, dynamical systems, partial differential equations, nonequilibrium statistical physics, geophysics and climate.
Donald Geman
Professor: image analysis, statistical learning, bioinformatics.
Yannis Kevrekidis
Bloomberg Distinguished Professor: algorithms, data, and the computer-assisted modeling of complex dynamical systems.
Sunil Kumar
Professor, Provost and Sr Vice President for Academic Affairs: optimizing manufacturing systems, service operations, and communications networks; and on applying optimization methods and control theory to various managerial problems.

Mauro Maggioni
Bloomberg Distinguished Professor: analysis, partial differential equations, algebraic topology, big data, data intensive computation, harmonic analysis over manifolds and over discrete structures.

Carey E. Priebe
Professor: statistics, image analysis, pattern recognition.
John C. Wierman
Professor: probability, statistics, discrete mathematics, percolation theory, stochastic processes.

Associate Professors
Amitabh Basu
Associate Professor: optimization, discrete and combinatorial geometry, convex analysis, operations research.
Tamas Budavari
Associate Professor: computational statistics, Bayesian inference, low-dimensional embeddings, streaming algorithms, parallel processing on GPUs, scientific databases, survey astronomy.

Assistant Professors
Maxim Bichuch
Assistant Professor: financial mathematics, utility optimization, market with transaction costs, counterparty risk, valuation adjustments
Nicolas Charon
Assistant Professor: shape analysis, image analysis, Riemannian and discrete geometry.
Edinah Gnang
Assistant Professor: discrete mathematics, graph theory, multilinear algebra, image analysis, experimental math.
Daniel P. Robinson
Assistant Professor: optimization, numerical analysis, matrix analysis, complementarity problems.
Yanxun Xu
Assistant Professor: Bayesian statistics, cancer genomics, clinical trial design, graphical model, nonparametric Bayesian, statistical inference for big data analysis, high-throughput genomic data and proteomics data.
Research Professor
Helyette Geman
Research Professor: financial mathematics, commodities.

James C. Spall

Associate Research Professor
Minh Hai Tang
Associate Research Professor: statistical pattern recognition, high-dimensional data analysis.

Assistant Research Professor
Avanti Athreya
Assistant Research Professor: probability, stochastic processes.

Mengyang Gu
Assistant Research Professor: Bayesian analysis, uncertainty quantification, computer model emulation and calibration, spatial statistics, time series, robust analysis, graphical models.

Senior Lecturer
Beryl Castello
Senior Lecturer: operations research, optimization, facility location, inventory modeling.

Mario Micheli
Senior Lecturer: image processing, shape analysis, variational methods, and applied statistics.

John Miller
Senior Lecturer: financial mathematics, equity derivative trading and risk management, number theory.

Fred Torcaso
Senior Lecturer: stochastic processes, asymptotics, and partial differential equations.

Associate Research Scientist
Antwan D. Clark
Associate Research Scientist: high performance computing and resiliency analysis.

Assistant Research Scientist
Devrim Kaba
Assistant Research Scientist: statistics, dynamical systems, and optimization for security assessment in power systems.

Joint and Secondary Appointments
Gregory Chirikjian
Professor: Mechanical Engineering, computational structural biology, applied mathematics, robotics.

Takeru Igusa
Professor: Civil Engineering.

S. Rao Kosaraju
Edward J. Schaefer Professor: Computer Science, design of algorithms, parallel computation, pattern matching, robotics computational geometry.

Fei Lu
Assistant Professor: Mathematics.

Enrique Mallada
Assistant Professor: Electrical and Computer Engineering.

Michael I. Miller
Professor: Biomedical Engineering.

Jerry L. Prince
Professor: Electrical and Computer Engineering, multi-dimensional signal processing, medical imaging, computational geometry.

Suchi Saria
Assistant Professor: Computer Science.

Sauleh Siddiqui
Assistant Professor: Civil Engineering.

Joshua Vogelstein
Assistant Professor: Center for Imaging Science.

For current course information and registration go to https://sis.jhu.edu/classes/

Courses
EN.553.100. Introduction to Applied Mathematics and Statistics. 1.0 Credit.
A seminar-style series of lectures and assignments to acquaint the student with a range of intellectual and professional activities performed by applied mathematicians and statisticians. Problems arising in applied mathematics and statistics are presented by department faculty and outside speakers. Recommended Course Background: one semester of Calculus.
Instructor(s): M. Bichuch
Area: Engineering, Quantitative and Mathematical Sciences.

EN.553.105. Mathematics of Music. 3.0 Credits.
This course aims to promote students' understanding of some important mathematical concepts by focusing on music and the sounds made by musical instruments as an area of mathematical application. Students will be exposed to basic concepts in mathematics including Fourier series, linear algebra, fundamental ideas from signal processing, and stochastic process models. The structure, organization, and synthesis of sounds and combinations of sounds will be explored.
Instructor(s): D. Naiman
Area: Quantitative and Mathematical Sciences.
EN.553.171. Statistical Analysis I. 4.0 Credits.
First semester of a general survey of statistical methodology. Topics include descriptive statistics, introductory probability, conditional probability, random variables, expectation, sampling, the central limit theorem, classical and robust estimation, confidence intervals, and hypothesis testing. Case studies from psychology, epidemiology, economics and other fields serve to illustrate the underlying theory. Some use of Minitab, Excel or R, but no prior computing experience is necessary. Recommended Course Background: four years of high school mathematics. Students who may wish to undertake more than two semesters of probability and statistics should consider EN.553.420-EN.553.430.
Prerequisites: Statistics Sequence restriction: students who have completed AS.230.205 may not enroll.;Statistics Sequence restriction: students who have completed any of these courses may not register: EN.553.211 OR EN.553.230 OR EN.553.310 OR EN.553.311 OR EN.553.420 OR EN.553.430 OR EN.553.413 OR EN.560.435 OR AS.280.345 OR AS.200.314 OR AS.200.315 OR EN.560.348
Instructor(s): D. Athreya
Area: Engineering, Quantitative and Mathematical Sciences.
EN.553.112. Statistical Analysis II. 4.0 Credits.
Second semester of a general survey of statistical methodology. Topics include two-sample hypothesis tests, analysis of variance, linear regression, correlation, analysis of categorical data, and nonparametrics. Students who may wish to undertake more than two semesters of probability and statistics should strongly consider the EN.553.420-430 sequence.
Prerequisites: EN.553.111 OR AS.230.205 OR AS.280.345 OR credit for AP Statistics
Instructor(s): F. Torcaso
Area: Engineering, Quantitative and Mathematical Sciences.
EN.553.172. Honors Discrete Mathematics. 4.0 Credits.
Introduction to the mathematics of finite systems. Logic; Boolean algebra; induction and recursion; sets, functions, relations, equivalence, and partially ordered sets; elementary combinatorics; modular arithmetic and the Euclidean algorithm; polynomials rings, group theory; permutations groups and Galois theory; graph theory. Selected applications. The concept of a proof and development of the ability to recognize and construct proofs and analyze algorithms are part of the course. Recommended Course Background: Four years of high school mathematics.
Prerequisites: Students may not earn credit for both EN.553.171 and EN.553.172.;EN.553.172 may not be taken after EN.553.471 OR EN.553.472 OR EN.553.671 OR EN.553.672
Instructor(s): E. Gnang
Area: Quantitative and Mathematical Sciences.
EN.553.211. Probability and Statistics for the Life Sciences. 4.0 Credits.
This is an introduction to statistics aimed at students in the life sciences. The course will provide the necessary background in probability with treatment of independence, Bayes theorem, discrete and continuous random variables and their distributions. The statistical topics covered will include sampling and sampling distributions, confidence intervals and hypothesis testing for means, comparison of populations, analysis of variance, linear regression and correlation. Analysis of data will be done using Excel.
Prerequisites: AS.110.106 OR AS.110.108 OR AS.110.113;Statistics Sequence restriction: Students who have completed any of these courses may not register: EN.550.230 OR AS.280.345 OR AS.200.314 OR AS.200.315 OR EN.550.310 OR EN.550.311 OR EN.560.435 OR EN.550.420 OR EN.550.430 OR EN.560.348
Instructor(s): Staff
Area: Quantitative and Mathematical Sciences.
EN.553.230. Introduction to Biostatistics. 4.0 Credits.
A self-contained course covering various data analysis methods used in the life sciences. Topics include types of experimental data, numerical and graphical descriptive statistics, concepts of (and distinctions between) population and sample, basic probability, fitting curves to experimental data (regression analysis), comparing groups in populations (analysis of variance), methods of modeling probability (contingency tables and logistic regression). Prerequisite: 3 years of high school mathematics
Prerequisites: Statistics Sequence restriction: Students who have completed any of these courses may not enroll: EN.550.211 OR AS.280.345 OR AS.200.314 OR AS.200.315 OR EN.550.310 OR EN.550.311 OR EN.560.435 OR EN.550.420 OR EN.550.430 OR EN.560.348
Instructor(s): F. Torcaso
Area: Engineering, Quantitative and Mathematical Sciences.
EN.553.281. Introduction to Mathematical Programming. 4.0 Credits.
This course introduces a variety of techniques for solving optimization problems in engineering and science on a computer using MATLAB. Topics include the programming language MATLAB, as well as optimization theory, algorithms, and applications. MATLAB optimization tools will also be explored. Algorithms to be covered will include gradient descent, Newton’s method, and the simplex method. Applications will include constrained least squares regression, neural networks, and k-means clustering.
Prerequisites: (AS.110.107 OR AS.110.109 OR AS.110.113) AND (AS.110.201 OR AS.110.212 OR EN.553.291)
Instructor(s): M. Zhong
Area: Engineering, Quantitative and Mathematical Sciences.
EN.553.291. Linear Algebra and Differential Equations. 4.0 Credits.
An introduction to the basic concepts of linear algebra, matrix theory, and differential equations that are used widely in modern engineering and science. Intended for engineering and science majors whose program does not permit taking both AS.110.201 and AS.110.302.
Prerequisites: AS.110.107 OR AS.110.109 OR AS.110.113
Instructor(s): M. Micheli
Area: Engineering, Quantitative and Mathematical Sciences.

EN.553.310. Probability & Statistics. 4.0 Credits.
An introduction to probability and statistics at the calculus level, intended for engineering and science students planning to take only one course on the topics. Combinatorial probability, independence, conditional probability, random variables, expectation and moments, limit theory, estimation, confidence intervals, hypothesis testing, tests of means and variances, goodness-of-fit. Recommended co-requisite: multivariable calculus.
Prerequisites: (AS.110.106 OR AS.110.108) AND (AS.110.107 OR AS.110.109) OR AS.110.113; Statistics Sequence restriction: Students who have completed any of these courses may not register: EN.553.311 OR EN.560.435 OR EN.553.420 OR EN.553.430 OR EN.560.348
Instructor(s): K. Lahouel
Area: Engineering, Quantitative and Mathematical Sciences.

EN.553.311. Probability and Statistics for the Biological Sciences and Engineering. 4.0 Credits.
An introduction to probability and statistics at the calculus level, intended for students in the biological sciences planning to take only one course on the topics. Combinatorial probability, independence, conditional probability, random variables, expectation and moments, limit theory, estimation, confidence intervals, hypothesis testing, tests of means and variances, goodness-of-fit will be covered. Recommended Course Corequisite: AS.110.202
Prerequisites: (AS.110.106 OR AS.110.108) AND (AS.110.107 OR AS.110.109) OR AS.110.113; Statistics Sequence restriction: students who have completed any of these courses may not register: EN.553.310 OR EN.560.435 OR EN.553.420 OR EN.553.430 OR EN.560.348
Instructor(s): F. Torcaso
Area: Engineering, Quantitative and Mathematical Sciences.

EN.553.361. Introduction to Optimization. 4.0 Credits.
An introductory survey of optimization methods, supporting mathematical theory and concepts, and application to problems of planning, design, prediction, estimation, and control in engineering, management, and science. Study of varied optimization techniques including linear programming, network-problem methods, dynamic programming, integer programming, and nonlinear programming. Students should be familiar with computing and linear algebra. Recommended Course Background: one year of calculus
Prerequisites: (AS.110.107 OR AS.110.109 OR AS.110.113) AND (EN.553.291 OR AS.110.201 OR AS.110.212)
Instructor(s): D. Fishkind
Area: Engineering, Quantitative and Mathematical Sciences.

EN.553.362. Introduction to Optimization II. 4.0 Credits.
An introductory survey of optimization methods, supporting mathematical theory and concepts, and application to problems of planning, design, prediction, estimation, and control in engineering, management, and science. Study of varied optimization techniques including linear programming, network-problem methods, dynamic programming, integer programming, and nonlinear programming. Appropriate for undergraduate students and graduate students without the mathematical background required for EN.553.761.
Prerequisites: EN.550.361 AND (AS.110.202 OR AS.110.211)
Instructor(s): D. Fishkind
Area: Engineering, Quantitative and Mathematical Sciences.

EN.553.385. Scientific Computing: Linear Algebra. 4.0 Credits.
A first course on computational linear algebra and applications. Topics include floating-point arithmetic, algorithms and convergence, Gaussian elimination for linear systems, matrix decompositions (LU, Cholesky, QR), iterative methods for systems (Jacobi, Gauss–Seidel), and approximation of eigenvalues (power method, QR-algorithm). Theoretical topics such as vector spaces, inner products, norms, linear operators, matrix norms, eigenvalues, and canonical forms of matrices (Jordan, Schur) are reviewed as needed. Matlab is used to solve all numerical exercises; no previous experience with computer programming is needed.
Prerequisites: (EN.550.291 OR AS.110.201 OR AS.110.212) AND (AS.110.202 OR AS.110.211)
Instructor(s): Staff
Area: Quantitative and Mathematical Sciences.

EN.553.386. Scientific Computing: Linear Algebra. 4.0 Credits.
A first course on computational linear algebra and applications. Topics include floating-point arithmetic, algorithms and convergence, Gaussian elimination for linear systems, matrix decompositions (LU, Cholesky, QR), iterative methods for systems (Jacobi, Gauss–Seidel), and approximation of eigenvalues (power method, QR-algorithm). Theoretical topics such as vector spaces, inner products, norms, linear operators, matrix norms, eigenvalues, and canonical forms of matrices (Jordan, Schur) are reviewed as needed. Matlab is used to solve all numerical exercises; no previous experience with computer programming is required.
Prerequisites: (EN.553.291 OR AS.110.201 OR AS.110.212) AND (AS.110.202 OR AS.110.211)
Instructor(s): G. Eyink
Area: Engineering, Quantitative and Mathematical Sciences.
EN.553.386. Scientific Computing: Differential Equations. 4.0 Credits.
A first course on computational differential equations and applications. Topics include floating-point arithmetic, algorithms and convergence, root-finding (midpoint, Newton, and secant methods), numerical differentiation and integration, and numerical solution of initial value problems (Runge–Kutta, multistep, extrapolation methods, stability, implicit methods, and stiffness). Theoretical topics such as existence, uniqueness, and stability of solutions to initial-value problems, conversion of higher order/ non-autonomous equations to systems, etc., will be covered as needed. Matlab is used to solve all numerical exercises; no previous experience with computer programming is required.
Prerequisites: (AS.110.202 OR AS.110.211) AND (EN.550.291 OR AS.110.302 OR AS.110.306).
Instructor(s): G. Eyink
Area: Engineering, Quantitative and Mathematical Sciences.

EN.553.388. Scientific Computing: Differential Equations in Vector Spaces. 4.0 Credits.
A first course on computational differential equations in vector spaces and applications, a continuation of EN.553.385. Topics include root-finding for nonlinear systems of equations (bisection, Newton, and secant methods), numerical differentiation and integration, and numerical solution of initial-value problems (Runge–Kutta, multistep, extrapolation methods, stability, implicit methods, and stiffness) and boundary-value problems (shooting method, relaxation) for ordinary differential equations in finite-dimensional vector spaces. Theoretical topics such as existence, uniqueness, and stability of solutions to initial-value problems, conversion of higher-order/non-autonomous equations to systems, etc., will be covered as needed. Matlab is used to solve all numerical exercises.
Prerequisites: Prerequisites: EN.550.385 AND (EN.550.291 OR AS.110.302 OR AS.110.306)
Instructor(s): G. Eyink
Area: Engineering, Quantitative and Mathematical Sciences.

EN.553.391. Dynamical Systems. 4.0 Credits.
Mathematical concepts and methods for describing and analyzing linear and nonlinear systems that evolve over time. Topics include boundedness, stability of fixed points and attractors, feedback, optimality, Liapounov functions, bifurcation, chaos, and catastrophes. Examples drawn from population growth, economic behavior, physical and engineering systems. The main mathematical tools are linear algebra and basic differential equations.
Prerequisites: EN.553.291 OR AS.110.201 OR AS.110.211
Instructor(s): X. Ye
Area: Engineering, Quantitative and Mathematical Sciences.

EN.553.400. Mathematical Modeling and Consulting. 4.0 Credits.
Creating, analyzing and evaluating optimization and mathematical models using case studies. Project-oriented practice and guidance in modeling techniques, with emphasis on communication of methods and results. Applications may include transportation networks, scheduling, industrial processes, and telecommunications. Computation will be emphasized throughout using MATLAB.
Prerequisites: EN.553.361 OR EN.553.362; Students may receive credit for EN.550.400/EN.553.400 or EN.553.600, but not both.
Instructor(s): B. Castello
Area: Engineering, Quantitative and Mathematical Sciences.

EN.553.413. Applied Statistics and Data Analysis. 4.0 Credits.
An introduction to basic concepts, techniques, and major computer software packages in applied statistics and data analysis. Topics include numerical descriptive statistics, observations and variables, sampling distributions, statistical inference, linear regression, multiple regression, design of experiments, nonparametric methods, and sample surveys. Real-life data sets are used in lectures and computer assignments. Intensive use of statistical packages such as S+ to analyze data.
Prerequisites: EN.553.112 OR EN.553.310 OR EN.553.311 OR EN.553.420; Students may receive credit for EN.550.413/EN.553.413 or EN.553.613, but not both.
Instructor(s): M. Tang
Area: Engineering, Quantitative and Mathematical Sciences.

EN.553.414. Applied Statistics and Data Analysis II. 3.0 Credits.
Part II of a sequence on data analysis and linear models. Topics include categorical and discrete data analysis, mixed models, semiparametric and nonparametric regression, and generalized additive models. Applications of these methods using the R environment for statistical computing will be emphasized.
Prerequisites: EN.550.413; Students may receive credit for EN.550.414/EN.553.414 or EN.553.614, but not both.
Instructor(s): M. Tang
Area: Engineering, Quantitative and Mathematical Sciences.

EN.553.416. Introduction to Statistical Learning, Data Analysis and Signal Processing. 4.0 Credits.
Introduction to high dimensional data sets: key problems in statistical and machine learning. Geometric aspects. Principal component analysis, linear dimension reduction, random projections. Concentration phenomena: examples and basic inequalities. Metric spaces and embeddings thereof. Kernel methods. Nonlinear dimension reduction, manifold models. Regression. Vector spaces of functions, linear operators, projections. Orthonormal bases; Fourier and wavelet bases, and their use in signal processing and time series analysis. Basic approximation theory. Linear models, least squares. Bias and variance tradeoffs, regularization. Sparsity and compressed sensing. Multiscale methods. Graphs and networks. Random walks on graphs, diffusions, page rank. Block models. Spectral clustering, classification, semi-supervised learning. Algorithmic and computational aspects of the above will be consistently in focus, as will be computational experiments on synthetic and real data. Linear algebra will be used throughout the course, as will multivariable calculus and basic probability (discrete random variables). Basic experience in programming in C or MATLAB or R or Octave. Recommended Course Background: More than basic programming experience in Matlab or R; some more advanced probability (e.g. continuous random variables), some signal processing (e.g. Fourier transform, discrete and continuous). Co-listed with AS.110.446
Prerequisites: (AS.110.201 OR AS.110.212) AND (EN.550.310 OR EN.550.311 OR EN.550.420) AND (AS.110.202 OR AS.110.211)
Instructor(s): M. Maggioni
Area: Engineering, Quantitative and Mathematical Sciences.
EN.553.417. Mathematical Modeling: Statistical Learning. 3.0 Credits.
Students will work independently or in groups on two or more projects using and developing machine learning methods such as linear and generalized linear regression, shrinkage method, Bayesian decision theory, variable selection, clustering, dimension reduction, functional data analysis, kernel smoothing methods and so on. These concepts will be briefly discussed in class, but some basic knowledge about them is expected. Some usual coding methods such as R, python, Matlab and C++ will also be discussed in class. Successful works could gradually turn into a part of an undergraduate or graduate thesis, or research papers. This course emphasizes on both mathematical reasons behind a model and computational skills to implement.
Prerequisites: EN.550.436 or EN.550.413 or EN.550.430 or EN.550.630 or EN.550.632
Instructor(s): M. Gu
Area: Quantitative and Mathematical Sciences.

EN.553.420. Introduction to Probability. 4.0 Credits.
Probability and its applications, at the calculus level. Emphasis on techniques of application and on rigorous mathematical demonstration. Probability, combinatorial probability, random variables, distribution functions, important probability distributions, independence, conditional probability, moments, covariance and correlation, limit theorems. Students initiating graduate work in probability or statistics should enroll in EN.553.620 or EN.553.720. Prerequisites: one year of calculus.
Corequisites: multivariable calculus and linear algebra
Prerequisites: AS.110.107 OR AS.110.109 OR AS.110.113; Students may receive credit for EN.550.420/EN.553.420 or EN.553.620, but not both.; AS.110.201 OR AS.110.202 OR AS.110.211 OR AS.110.212, can be taken concurrently.
Instructor(s): J. Wierman
Area: Engineering, Quantitative and Mathematical Sciences.

EN.553.426. Introduction to Stochastic Processes. 4.0 Credits.
Mathematical theory of stochastic processes. Emphasis on deriving the dependence relations, statistical properties, and sample path behavior including random walks, Markov chains (both discrete and continuous time), Poisson processes, martingales, and Brownian motion. Applications that illuminate the theory. Students may receive credit for only one of EN.553.426, EN.553.427, EN.553.626, or EN.553.627.
Prerequisites: (EN.550.420 OR EN.553.420) AND (EN.550.291 OR AS.110.201 OR AS.110.212); Students may receive credit for EN.550.426/EN.553.426 or EN.553.626, but not both.
Instructor(s): J. Wierman
Area: Engineering, Quantitative and Mathematical Sciences.

EN.553.427. Stochastic Processes and Applications to Finance. 4.0 Credits.
A basic knowledge of stochastic calculus and Brownian motion is assumed. Topics include stochastic differential equations, the Feynman-Kac formula and connections to partial differential equations, changes of measure, fundamental theorems of asset pricing, martingale representations, first passage times and pricing of path-dependent options, and jump processes.
Prerequisites: EN.553.427 OR EN.553.627; Students may receive credit for EN.550.428/EN.553.428 or EN.553.628, but not both.
Instructor(s): J. Miller
Area: Quantitative and Mathematical Sciences.

EN.553.429. Introduction to Research in Discrete Probability. 3.0 Credits.
Aspects of the research process, including reading and writing mathematics, LaTeX, literature search, problem identification, problem-solving, oral presentations, Beamer, conference attendance, publication of results, and research ethics. An initial research experience, individually and/or in groups, with students identifying and developing projects in discrete mathematics and probability, such as percolation, random graphs, random walks, birthday problems, gambler's ruin, coupon collector problems, and self-avoiding walks. Instructor's permission required. Open only to undergraduates.
Prerequisites: EN.553.171 AND (EN.553.420 OR EN.553.620); Students may receive credit for EN.550.429/EN.553.429 or EN.553.629, but not both.
Instructor(s): J. Wierman
Area: Quantitative and Mathematical Sciences.

EN.553.430. Introduction to Statistics. 4.0 Credits.
Introduction to the basic principles of statistical reasoning and data analysis. Emphasis on techniques of application. Classical parametric estimation, hypothesis testing, and multiple decision problems; linear models, analysis of variance, and regression; nonparametric and robust procedures; decision-theoretic setting, Bayesian methods.
Prerequisites: (EN.553.420 OR EN.553.620) AND (AS.110.201 OR AS.110.212 OR EN.553.291); Students may receive credit for EN.550.430/EN.553.430 or EN.553.630, but not both.
Instructor(s): D. Athreya
Area: Engineering, Quantitative and Mathematical Sciences.

EN.553.431. Statistical Methods in Imaging. 3.0 Credits.
Denosing, segmentation, texture modeling, tracking, object recognition are challenging problems in imaging. We will present a collection of statistical models and methods in order to address these, including the EM algorithm, Maximum Entropy Modeling, Particle filtering, Markov Random Fields and Belief Propagation. Co-listed with EN.580.466. Some practice of Matlab or R is highly recommended.
Prerequisites: (AS.110.202 OR AS.110.211) AND (EN.550.310 OR EN.550.311 OR EN.550.420)
Instructor(s): Staff
Area: Engineering, Quantitative and Mathematical Sciences.
EN.553.433. Monte Carlo Methods. 3.0 Credits.
The objective of the course is to survey essential simulation techniques for popular stochastic models. The stochastic models may include classical time-series models, Markov chains and diffusion models. The basic simulation techniques covered will be useful in sample-generation of random variables, vectors and stochastic processes, and as advanced techniques, importance sampling, particle filtering and Bayesian computation may be discussed.
Prerequisites: Students may receive credit for EN550.433/EN.553.433 or EN.553.633, but not both.;EN.553.430 OR EN.553.630
Instructor(s): J. Spall
Area: Engineering, Quantitative and Mathematical Sciences.

EN.553.436. Data Mining. 4.0 Credits.
Data mining is a relatively new term used in the academic and business world, often associated with the development and quantitative analysis of very large databases. Its definition covers a wide spectrum of analytic and information technology topics, such as machine learning, artificial intelligence, statistical modeling, and efficient database development. This course will review these broad topics, and cover specific analytic and modeling techniques such as advanced data visualization, decision trees, neural networks, nearest neighbor, clustering, logistic regression, and association rules. Although some of the mathematics underlying these techniques will be discussed, our focus will be on the application of the techniques to real data and the interpretation of results. Because use of the computer is extremely important when "mining" large amounts of data, we will make substantial use of data mining software tools to learn the techniques and analyze datasets. Recommended Course Background: EN.553.413
Prerequisites: Students may receive credit for EN.550.436/EN.553.436 or EN.553.636, but not both.;( AS.110.202 OR AS.110.211 ) AND ( AS.110.201 OR AS.110.212 OR EN.550.291 )
Instructor(s): T. Budavari
Area: Engineering, Quantitative and Mathematical Sciences.

EN.553.439. Time Series Analysis. 3.0 Credits.
Time series analysis from the frequency and time domain approaches. Descriptive techniques; regression analysis; trends, smoothing, prediction; linear systems; serial correlation; stationary processes; spectral analysis.
Prerequisites: ( EN.553.310[C] OR EN.553.311 OR EN.553.420 OR EN.553.620 ) AND ( AS.110.201 OR AS.110.212 OR EN.553.291 );Students may receive credit for EN.550.439/EN.553.439 or EN.553.639, but not both.
Instructor(s): D. Naiman; F. Torcaso; M. Pemy
Area: Engineering, Quantitative and Mathematical Sciences.

EN.553.441. Equity Markets and Quantitative Trading. 3.0 Credits.
This course introduces equity markets from a mathematical point of view. The properties of equities and equity-linked instruments will be described. Several quantitative trading strategies will be studied. Order execution tactics and the effect of market structure will be analyzed. Students will select a specialized aspect of the equity markets to investigate and complete a related independent project.
Prerequisites: EN.553.442 OR EN.553.642 OR EN.553.444 OR EN.553.644 or instructor's permission.;Students may receive credit for EN.550.441/EN.553.441 or EN.553.641, but not both.
Instructor(s): J. Miller
Area: Engineering, Quantitative and Mathematical Sciences.

EN.553.442. Investment Science. 4.0 Credits.
This course offers a rigorous treatment of the subject of investment as a scientific discipline. Mathematics is employed as the main tool to convey the principles of investment science and their use to make investment calculations for good decision-making. Topics covered in the course include the basic theory of interest and its application to fixed-income securities, cash flow analysis and capital budgeting, mean-variance portfolio theory, and the associated capital asset pricing model, utility function theory and risk analysis, derivative securities and basic option theory, portfolio evaluation. The student is expected to be comfortable with the use of mathematics as a method of deduction and problem solving. Students may not receive credit for both EN.550.342 and EN.553.442
Prerequisites: Students may receive credit for only one of EN.550.342, EN.550.442, EN.553.442 or EN.553.642;( AS.110.107 OR AS.110.109 OR AS.110.113 ) AND ( EN.553.291 OR AS.110.201 OR AS.110.212 ) AND ( EN.553.310 OR EN.553.311 OR EN.553.420 OR EN.553.620 OR EN.550.430 EN.553.630)
Instructor(s): J. Miller
Area: Engineering, Quantitative and Mathematical Sciences.

EN.553.443. Financial Computing in C++. 4.0 Credits.
The first part of course, will introduce the basic concepts of C++ including variables, functions, pointers and references, function and operator overloading and along with inheritance and polymorphism, templates and the C++ Standard Library. Basic ideas of object-oriented design will be introduced. The second part of the course will cover computational techniques for solving mathematical problems arising in finance. Numerical solution of parabolic partial differential equations for option valuation and their relation to tree methods together with a basic introduction of concepts such as convergence and stability as applied to finite difference schemes. Prerequisites EN.553.427 Stochastic Processes and Applications to Finance. No prior experience with C/C++ is required.
Prerequisites: EN.550.427
Instructor(s): M. Bichuch
Area: Quantitative and Mathematical Sciences.

EN.553.444. Introduction to Financial Derivatives. 4.0 Credits.
This course will develop the mathematical concepts and techniques for modeling cash instruments and their hybrids and derivatives.
Prerequisites: Students may receive credit for EN.550.444/EN.553.444 or EN.553.644, but not both.;AS.110.302 AND EN.553.420
Instructor(s): D. Audley
Area: Engineering, Quantitative and Mathematical Sciences.

EN.553.445. Interest Rate and Credit Derivatives. 4.0 Credits.
Advances in corporate finance, investment practice and the capital markets have been driven by the development of a mathematically rigorous theory for financial instruments and the markets in which they trade. This course builds on the concepts, techniques, instruments and markets introduced in EN.553.444. In addition to new topics in credit enhancement and structured securities, the focus is expanded to include applications in portfolio theory and risk management, and covers some numerical and computational approaches.
Prerequisites: EN.553.444 OR EN.553.644;Students may receive credit for EN.550.445/EN.553.445 or EN.553.645, but not both.
Instructor(s): D. Audley
Area: Engineering, Quantitative and Mathematical Sciences.
EN.553.446. Risk Measurement/Management in Financial Markets. 4.0 Credits.
This course applies advanced mathematical techniques to the measurement, analysis, and management of risk. The focus is on financial risk. Sources of risk for financial instruments (e.g., market risk, interest rate risk, credit risk) are analyzed; models for these risk factors are studied and the limitations, shortcomings and compensatory techniques are addressed.
Prerequisites: Students may receive credit for EN.550.446/EN.553.446 or EN.553.646, but not both.;EN.553.444 OR EN.553.644
Instructor(s): D. Audley
Area: Engineering, Quantitative and Mathematical Sciences.

EN.553.447. Quantitative Portfolio Theory and Performance Analysis. 4.0 Credits.
This course focuses on modern quantitative portfolio theory, models, and analysis. Topics include intertemporal approaches to modeling and optimizing asset selection and asset allocation; benchmarks (indexes), performance assessment (including, Sharpe, Treynor and Jensen ratios) and performance attribution; immunization theorems; alpha-beta separation in management, performance measurement and attribution; Replicating Benchmark Index (RBI) strategies using cash securities / derivatives; Liability-Driven Investment (LDI); and the taxonomy and techniques of strategies for traditional management: Passive, Quasi-Passive (Indexing) Semi-Active (Immunization & Dedicated) Active (Scenario, Relative Value, Total Return and Optimization). In addition, risk management and hedging techniques are also addressed.
Prerequisites: Students may receive credit for 550.447/553.447 OR EN.553.647, but not both.
Instructor(s): D. Audley
Area: Engineering, Quantitative and Mathematical Sciences.

EN.553.448. Financial Engineering and Structured Products. 4.0 Credits.
This course focuses on structured securities and the structuring of aggregates of financial instruments into engineered solutions of problems in capital finance. Topics include the fundamentals of creating asset-backed and structured securities—including mortgage-backed securities (MBS), stripped securities, collateralized mortgage obligations (CMOs), and other asset-backed collateralized debt obligations (CDOs)—structuring and allocating cash-flows as well as enhancing credit; equity hybrids and convertible instruments; asset swaps, credit derivatives and total return swaps; assessment of structure-risk interest rate-risk and credit-risk as well as strategies for hedging these exposures; managing portfolios of structured securities; and relative value analysis (including OAS and scenario analysis).
Prerequisites: EN.550.444[C] OR EN.550.442[C]
Instructor(s): D. Audley
Area: Engineering, Quantitative and Mathematical Sciences.

EN.553.449. Advanced Equity Derivatives. 4.0 Credits.
This course will cover the pricing, trading and risk management of equity derivatives, with emphasis on more exotic derivatives such as path-dependent and multi-asset derivatives. The course will emphasize practical issues: students will build their own pricing and risk management tools, and gain experience simulating the dynamic hedging of a complex derivatives portfolio. Students will practice structuring and selling equity derivative products. Pricing issues such a model selection, unobervable input parameters and calibration will be discussed, and students will learn techniques to manage the often highly nonlinear and discontinuous risks associated with these products. The course will have a significant computing component: both in the classroom and as homework projects, students will use Excel, write VBA macros and write and call C++ routines in the Microsoft Windows environment (which is the most common computing environment used by the financial industry).
Prerequisites: Students may receive credit for EN.550.449/EN.553.449 or EN.553.649, but not both.;EN.553.444 OR EN.553.644
Instructor(s): J. Miller
Area: Engineering, Quantitative and Mathematical Sciences.

EN.553.450. Computational Molecular Medicine. 4.0 Credits.
Computational systems biology has emerged as the dominant framework for analyzing high-dimensional "omics" data in order to uncover the relationships among molecules, networks and disease. In particular, many of the core methodologies are based on statistical modeling, including machine learning, stochastic processes and statistical inference. We will cover the key aspects of this methodology, including measuring associations, testing multiple hypotheses, and learning predictors, Markov chains and graphical models. In addition, by studying recent important articles in cancer systems biology, we will illustrate how this approach enhances our ability to annotate genomes, discover molecular disease networks, detect disease, predict clinical outcomes, and characterize disease progression. Whereas a good foundation in probability and statistics is necessary, no prior exposure to molecular biology is required (although helpful).
Prerequisites: ( EN.553.420 OR EN.553.620 ) AND ( EN.553.430 OR EN.553.630 ) OR equivalent courses in probability and statistics.;Students may receive credit for EN.550.450/EN.553.450 or EN.553.650, but not both.
Instructor(s): D. Geman; J. Bader
Area: Engineering, Quantitative and Mathematical Sciences.

EN.553.453. Mathematical Game Theory. 4.0 Credits.
Mathematical analysis of cooperative and noncooperative games. Theory and solution methods for matrix game (two players, zero-sum payoffs, finite strategy sets), games with a continuum of strategies, N-player games, games in rule-defined form. The roles of information and memory. Selected applications to economic, recreational, and military situations. Prereq: Multivariable Calculus, probability, linear algebra.
Prerequisites: Students may receive credit for EN.550.453/EN.553.453 or EN.553.653, but not both.;( AS.110.202 OR AS.110.211 ) AND ( EN.550.420 OR EN.553.620 ) AND ( EN.550.291 OR AS.110.201 OR AS.110.212 )
Instructor(s): B. Castello
Area: Engineering, Quantitative and Mathematical Sciences.

EN.553.457. Topics in Operations Research. 1.5 Credits.
Study in depth of a special mathematical or computational area of operations research, or a particular application area. Recent topics: decision theory, mathematical finance, optimization software.
Instructor(s): B. Castello
Area: Engineering, Quantitative and Mathematical Sciences.
EN.553.461. Optimization in Finance. 4.0 Credits.
A survey of many of the more important optimization methods and tools that are found to be useful in financial applications.
Prerequisites: Students may receive credit for EN.550.461/EN.553.461 or EN.553.661, but not both.;EN.553.442 OR EN.553.642 OR EN.553.444 OR EN.553.644
Instructor(s): B. Castello
Area: Engineering, Quantitative and Mathematical Sciences.
EN.553.463. Network Models in Operations Research. 4.0 Credits.
In-depth mathematical study of network flow models in operations research, with emphasis on combinatorial approaches for solving them. Introduction to techniques for constructing efficient algorithms, and to some related data structures, used in solving shortest-path, maximum-volume, flow, and minimum-cost flow problems. Emphasis on linear models and flows, with brief discussion of non-linear models and network design.
Prerequisites: Students may receive credit for EN.550.463/EN.553.463 or EN.553.663, but not both.;EN.553.361 OR EN.553.661 OR EN.553.761 OR EN.553.461
Instructor(s): B. Castello
Area: Engineering, Quantitative and Mathematical Sciences.
EN.553.465. Introduction to Convexity. 4.0 Credits.
Convexity is a simple mathematical concept that has become central in a diverse range of applications in engineering, science and business applications. Our main focus from the applications perspective will be the use of convexity within optimization problems, where convexity plays a key role in identifying the "easy" problems from the "hard" ones. The course will have an equal emphasis on expositing the rich mathematical structure of the field itself (properties of convex sets, convex functions, Helly-Caratheodory-Radon type theorems, polarity/duality, subdifferential calculus, polyhedral theory), and demonstrating how these ideas can be leveraged to model and solve optimization problems (via a detailed study of linear programming and basics of nonlinear convex optimization).
Recommend Course Background: Familiarity with basic real analysis, linear algebra.
Prerequisites: Students may receive credit for EN.550.465/EN.553.465 or EN.553.665, but not both.
Instructor(s): A. Basu
Area: Engineering, Quantitative and Mathematical Sciences.
EN.553.471. Combinatorial Analysis. 4.0 Credits.
Recommended Course Background: AS.553.291 or AS.110.201
Prerequisites: Students may receive credit for EN.550.471/EN.553.471 or EN.550.671/EN.553.671, but not both.;(AS.110.107 OR AS.110.109 OR AS.110.113) AND (AS.110.201 OR AS.110.212 OR EN.553.291)
Corequisites: EN.553.171 may not be taken concurrently with EN.553.471 or EN.553.472.
Instructor(s): E. Scheinerman
Area: Quantitative and Mathematical Sciences.
EN.553.472. Graph Theory. 4.0 Credits.
Study of systems of "vertices" with some pairs joined by "edges." Theory of adjacency, connectivity, traversability, feedback, and other concepts underlying properties important in engineering and the sciences. Topics include paths, cycles, and trees; routing problems associated with Euler and Hamilton; design of graphs realizing specified incidence conditions and other constraints. Attention directed toward problem solving, algorithms, and applications. One or more topics taken up in greater depth.
Prerequisites: EN.550.291 OR AS.110.201 OR AS.110.212; Students may receive credit for EN.550.472/EN.553.472 or EN.553.672, but not both.
Corequisites: EN.550.171 may not be taken concurrently with EN.550.471 or EN.550.472
Instructor(s): E. Gnang
Area: Quantitative and Mathematical Sciences.
EN.553.473. Introduction to Nonlinear Dynamics and Chaos. 3.0 Credits.
An introduction to the phenomenology of nonlinear dynamic behavior with emphasis on models of actual physical, chemical, and biological systems, involving an interdisciplinary approach to ideas from mathematics, computing, and modeling. The common features of the development of chaotic behavior in both mathematical models and experimental studies are stressed, and the use of modern data-mining tools to analyze dynamic data will be explored. Some computing experience is desirable. Emphasis will be placed on the geometric/visual computer-aided description and understanding of dynamics and chaos.
Prerequisites: Students may receive credit for only one of EN.553.473 OR EN.553.673 OR EN.550.468 OR EN.540.668.;(AS.110.201 OR AS.110.212) AND (AS.110.302 OR AS.110.306)) OR EN.553.291
Instructor(s): Y. Kevrekidis
Area: Engineering, Quantitative and Mathematical Sciences.
EN.553.485. Introduction to Harmonic Analysis and Its Applications. 4.0 Credits.
The course is an introduction to methods in harmonic analysis, in particular Fourier series, Fourier integrals, and wavelets. These methods will be introduced rigorously, together with their motivations and applications to the analysis of basic partial differential equations and integral kernels, signal processing, inverse problems, and statistical/machine. Co-listed with EN.553.685 and AS.110.433
Prerequisites: (AS.110.201 OR AS.110.212 OR EN.550.291/EN.553.291) AND (AS.110.202 OR AS.110.211) AND (AS.110.405 OR AS.110.415); Students may receive credit for only one of the following: AS.110.433, EN.553.485, or EN.553.685.
Instructor(s): M. Maggioni
Area: Quantitative and Mathematical Sciences.
EN.553.487. Numerical Methods for Financial Mathematics. 3.0 Credits.
Diffusion processes described by stochastic differential equations (SDEs) play an important role in the world of finance; one important tool in the study of complex SDEs is numerical simulation. In this class we concentrate on the numerical integration of SDEs, which requires a more complex mathematical construction than the integration of ordinary differential equations (ODEs). The algorithms for approximating SDE solutions are constructed on the basis of stochastic Taylor expansions, which can become particularly elaborate for systems with multiple noise sources. We propose to follow in detail all the steps from writing down an SDE to writing and running the computer code that will generate a "solution" of that SDE with a well-defined error. Python will be used for all applications, and more general programming concepts will be discussed as needed.
Instructor(s): Staff
Area: Quantitative and Mathematical Sciences.
EN.553.488. Financial Computing I. 3.0 Credits.
This course is aimed for student who need to develop the ability to use programming languages to solve data analytic problems that are likely to arise in financial applications. The C programming language will be introduced, and students will be exposed to some of the more useful C++ enhancements. The Python language will be introduced as well. Students should be comfortable using computers but no prior programming background is required. Some finance background is helpful but not necessary.
Prerequisites: Students may receive credit for EN.550.488/EN.553.488 or EN.553.688, but not both.;EN.553.310 OR EN.553.311 OR (EN.553.420 EN.553.620) AND (EN.553.430 OR EN.553.630)
Instructor(s): D. Naiman
Area: Engineering, Quantitative and Mathematical Sciences.

EN.553.492. Mathematical Biology. 3.0 Credits.
This course will examine the mathematical methods relevant to modeling biological phenomena, particularly dynamical systems and probability. Topics include ordinary differential equations and their simulation; stability and phase plane analysis; branching processes; Markov chains; and stochastically perturbed systems. Biological applications will be drawn from population growth, predator-prey dynamics, epidemiology, genetics, intracellular transport, and neuroscience.
Prerequisites: (EN.553.420 OR EN.553.620) AND (AS.110.201 OR AS.110.212) AND (AS.110.302 OR AS.110.306 OR EN.553.291); Students may receive credit for EN.550.492/EN.553.492 or EN.553.692, but not both.
Instructor(s): D. Athreya
Area: Natural Sciences, Quantitative and Mathematical Sciences.

EN.553.493. Mathematical Image Analysis. 3.0 Credits.
This course gives an overview of various mathematical methods related to several problems encountered in image processing and analysis, and presents numerical schemes to address them. It will focus on problems like image denoising and deblurring, contrast enhancement, segmentation and registration. The different mathematical concepts shall be introduced during the course; they include in particular functional spaces such as Sobolev and BV, Fourier and wavelet transforms, as well as some notions from convex optimization and numerical analysis. Most of such methods will be illustrated with algorithms and simulations on discrete images, using MATLAB. Prerequisites: linear algebra, multivariate calculus, basic programming in MATLAB. Recommended Course Background: Real analysis
Prerequisites: (AS.110.202 OR AS.110.211) AND (EN.550.291 OR AS.110.201 OR AS.110.212); Students may receive credit for EN.550.493/EN.553.493 or EN.553.693, but not both.
Instructor(s): P. Escande
Area: Engineering, Quantitative and Mathematical Sciences.

EN.553.494. Applied and Computational Linear Algebra. 3.0 Credits.
In this seminar we plan to discuss generalizations of theorems and algorithms from matrix theory to hypermatrices. More specifically the seminar will discuss hypermatrix/tensor algebras, rank, spectra and transforms. Using the python friendly free open-source mathematics software SageMath and the hypermatrix algebra package we will discuss applications of hypermatrices to combinatorics, machine learning and data analysis. Preliminary knowledge of the Python language is not required.
Prerequisites: Students may receive credit for EN.550.494/EN.553.494 or EN.553.694, but not both.; AS.110.201 OR AS.110.212 OR EN.550.291
Instructor(s): E. Gnang
Area: Quantitative and Mathematical Sciences.

EN.553.500. Undergraduate Research. 1.0 - 3.0 Credits.
Reading, research, or project work for undergraduate students. Pre-arranged individually between students and faculty.
Instructor(s): D. Fishkind; E. Scheinerman; J. Wierman; T. Budavari.

EN.553.501. Senior Thesis. 3.0 Credits.
Instructor(s): Staff.

EN.553.502. Undergraduate Independent Study. 1.0 - 3.0 Credits.
Reading, research, or project work for undergraduate students. Pre-arranged individually between students and faculty. Recent topics and activities: percolation models, data analysis, course development assistance, and dynamical systems.
Instructor(s): Staff.

EN.553.503. Preparation for Research. 1.0 Credit.
Primarily an independent study course. Readings, assignments, and discussion to prepare students for research in applied mathematics and statistics. Topics include the research process, problem-solving, mathematical writing, LaTeX, Beamer; reading mathematics, literature search, oral presentations, REU programs, and the publication process. Brief meetings to be arranged. Students are expected to spend 3 to 4 hours per week in addition to the meetings. Grading is Satisfactory/Unsatisfactory only.
Instructor(s): J. Wierman.

EN.553.505. Applied Mathematics Pedagogy. 3.0 Credits.
Instructor Permission Required - Opportunity for students to participate
Instructor(s): B. Castello.

EN.553.512. Group Undergraduate Research. 1.0 - 3.0 Credits.
Reading, research, or project work for undergraduate students. Pre-arranged meetings between students and faculty. This section has a weekly research group meeting that students are expected to attend.
Instructor(s): D. Fishkind; E. Fertig; E. Scheinerman.

EN.553.552. Undergraduate Internship. 1.0 Credit.
Instructor(s): Staff.

EN.553.590. Internship - Summer. 1.0 Credit.
Instructor(s): Staff.

EN.553.597. Research-Summer. 3.0 Credits.
Instructor(s): Staff.

EN.553.599. Independent Study. 3.0 Credits.
Instructor(s): D. Fishkind; E. Scheinerman; F. Torcaso.

EN.553.600. Mathematical Modeling and Consulting. 4.0 Credits.
Creating, analyzing and evaluating optimization and mathematical models using case studies. Project-oriented practice and guidance in modeling techniques, with emphasis on communication of methods and results. Applications may include transportation networks, scheduling, industrial processes, and telecommunications. Computation will be emphasized throughout using MATLAB. Recommended Course Background: EN.553.361 OR EN.553.362.
Prerequisites: Students may receive credit for EN.550.400/EN.553.400 or EN.553.600, but not both.
Instructor(s): B. Castello
Area: Engineering, Quantitative and Mathematical Sciences.
EN.553.613. Applied Statistics and Data Analysis. 4.0 Credits.
An introduction to basic concepts, techniques, and major computer
software packages in applied statistics and data analysis. Topics include
numerical descriptive statistics, observations and variables, sampling
distributions, statistical inference, linear regression, multiple regression,
design of experiments, nonparametric methods, and sample surveys.
Real-life data sets are used in lectures and computer assignments.
Intensive use of statistical packages such as S+ to analyze data.
Recommend Course Background: EN.553.112 OR EN.553.310 OR
EN.553.311 OR EN.553.420.
Prerequisites: Students may receive credit for EN.550.413/EN.553.413 or
EN.553.613, but not both.
Instructor(s): M. Tang
Area: Engineering, Quantitative and Mathematical Sciences.

EN.553.614. Applied Statistics and Data Analysis II. 3.0 Credits.
Part II of a sequence on data analysis and linear models. Topics include
categorical and discrete data analysis, mixed models, semiparametric
and nonparametric regression, and generalized additive models.
Applications of these methods using the R environment for statistical
computing will be emphasized.
Prerequisites: Students may receive credit for EN.550.414/EN.553.414 or
EN.553.614, but not both.
Instructor(s): M. Tang
Area: Engineering, Quantitative and Mathematical Sciences.

EN.553.620. Introduction to Probability. 4.0 Credits.
Probability and its applications, at the calculus level. Emphasis on
techniques of application and on rigorous mathematical demonstration.
Probability, combinatorial probability, random variables, distribution
functions, important probability distributions, independence, conditional
probability, moments, covariance and correlation, limit theorems. Auditors
are not permitted. Recommended course background: (AS.110.107 or
AS.110.109 or AS.110.113) and previously or concurrently (AS.110.202 or
AS.110.201 or AS.110.212).
Prerequisites: Students may receive credit for EN.550.420/EN.553.420 or
EN.553.620, but not both.
Instructor(s): J. Wierman
Area: Engineering, Quantitative and Mathematical Sciences.

EN.553.621. Introduction to Stochastic Processes. 4.0 Credits.
Mathematical theory of stochastic processes. Emphasis on deriving
the dependence relations, statistical properties, and sample path
behavior including random walks, Markov chains (both discrete and
continuous time), Poisson processes, martingales, and Brownian motion.
Applications that illuminate the theory. Students may receive credit
for only one of EN.553.426, EN.553.427, EN.553.626, or EN.553.627.
Recommended course background: EN.553.620 and (EN.553.291 OR
AS.110.201 OR AS.110.212).
Prerequisites: Students may receive credit for EN.550.426/EN.553.426 or
EN.553.626, but not both.
Instructor(s): J. Wierman
Area: Engineering, Quantitative and Mathematical Sciences.

EN.553.622. Introduction to Stochastic Processes and Applications to Finance I. 4.0 Credits.
A development of stochastic processes with substantial emphasis on
the processes, concepts, and methods useful in mathematical finance.
Relevant concepts from probability theory, particularly conditional
probability and conditional expectation, will be briefly reviewed. Important
concepts in stochastic processes will be introduced in the simpler
setting of discrete-time processes, including random walks, Markov
chains, and discrete-time martingales, then used to motivate more
advanced material. Most of the course will concentrate on continuous-
time stochastic processes, particularly martingales, Brownian motion,
diffusions, and basic tools of stochastic calculus. Examples will focus
on applications in finance, economics, business, and actuarial science.
Recommend Course Background: EN.553.620.
Prerequisites: Students may receive credit for only one of EN.550.427,
EN.553.427, EN.553.627.
Instructor(s): M. Bichuch
Area: Quantitative and Mathematical Sciences.

EN.553.623. Introduction to Stochastic Processes and Applications to Finance II. 4.0 Credits.
A basic knowledge of stochastic calculus and Brownian motion is
assumed. Topics include stochastic differential equations, the Feynman-
Kac formula and connections to partial differential equations, changes
of measure, fundamental theorems of asset pricing, martingale
representations, first passage times and pricing of path-dependent
options, and jump processes.
Prerequisites: Students may receive credit for EN.550.428/EN.553.428 or
EN.553.628, but not both.
Instructor(s): J. Miller
Area: Quantitative and Mathematical Sciences.

EN.553.624. Introduction to Research in Discrete Probability. 3.0 Credits.
An introduction to basic concepts, techniques, and major computer
software packages in applied statistics and data analysis. Emphasis on
techniques of application and on rigorous mathematical demonstration.
Probability, combinatorial probability, random variables, distribution
functions, important probability distributions, independence, conditional
probability, moments, covariance and correlation, limit theorems. Auditors
are not permitted. Recommended course background: (AS.110.107 or
AS.110.109 or AS.110.113) and previously or concurrently (AS.110.202 or
AS.110.201 or AS.110.212).
Prerequisites: Students may receive credit for EN.550.420/EN.553.420 or
EN.553.620, but not both.
Instructor(s): M. Tang
Area: Engineering, Quantitative and Mathematical Sciences.

EN.553.625. Introduction to Research in Discrete Probability II. 3.0 Credits.
Mathematical theory of stochastic processes. Emphasis on deriving
the dependence relations, statistical properties, and sample path
behavior including random walks, Markov chains (both discrete and
continuous time), Poisson processes, martingales, and Brownian motion.
Applications that illuminate the theory. Students may receive credit
for only one of EN.553.426, EN.553.427, EN.553.626, or EN.553.627.
Recommended course background: EN.553.620 and (EN.553.291 OR
AS.110.201 OR AS.110.212).
Prerequisites: Students may receive credit for EN.550.426/EN.553.426 or
EN.553.626, but not both.
Instructor(s): J. Wierman
Area: Engineering, Quantitative and Mathematical Sciences.

EN.553.626. Stochastic Processes and Applications to Finance. 4.0 Credits.
A development of stochastic processes with substantial emphasis on
the processes, concepts, and methods useful in mathematical finance.
Relevant concepts from probability theory, particularly conditional
probability and conditional expectation, will be briefly reviewed. Important
concepts in stochastic processes will be introduced in the simpler
setting of discrete-time processes, including random walks, Markov
chains, and discrete-time martingales, then used to motivate more
advanced material. Most of the course will concentrate on continuous-
time stochastic processes, particularly martingales, Brownian motion,
diffusions, and basic tools of stochastic calculus. Examples will focus
on applications in finance, economics, business, and actuarial science.
Recommend Course Background: EN.553.620.
Prerequisites: Students may receive credit for only one of EN.550.427,
EN.553.427, EN.553.627.
Instructor(s): M. Bichuch
Area: Quantitative and Mathematical Sciences.

EN.553.627. Stochastic Processes and Applications to Finance II. 4.0 Credits.
A basic knowledge of stochastic calculus and Brownian motion is
assumed. Topics include stochastic differential equations, the Feynman-
Kac formula and connections to partial differential equations, changes
of measure, fundamental theorems of asset pricing, martingale
representations, first passage times and pricing of path-dependent
options, and jump processes.
Prerequisites: Students may receive credit for EN.550.428/EN.553.428 or
EN.553.628, but not both.
Instructor(s): J. Miller
Area: Quantitative and Mathematical Sciences.

EN.553.628. Introduction to Research in Discrete Probability. 3.0 Credits.
An introduction to basic concepts, techniques, and major computer
software packages in applied statistics and data analysis. Emphasis on
techniques of application and on rigorous mathematical demonstration.
Probability, combinatorial probability, random variables, distribution
functions, important probability distributions, independence, conditional
probability, moments, covariance and correlation, limit theorems. Auditors
are not permitted. Recommended course background: (AS.110.107 or
AS.110.109 or AS.110.113) and previously or concurrently (AS.110.202 or
AS.110.201 or AS.110.212).
Prerequisites: Students may receive credit for EN.550.420/EN.553.420 or
EN.553.620, but not both.
Instructor(s): J. Wierman
Area: Engineering, Quantitative and Mathematical Sciences.

EN.553.629. Introduction to Research in Discrete Probability II. 3.0 Credits.
Mathematical theory of stochastic processes. Emphasis on deriving
the dependence relations, statistical properties, and sample path
behavior including random walks, Markov chains (both discrete and
continuous time), Poisson processes, martingales, and Brownian motion.
Applications that illuminate the theory. Students may receive credit
for only one of EN.553.426, EN.553.427, EN.553.626, or EN.553.627.
Recommended course background: EN.553.620 and (EN.553.291 OR
AS.110.201 OR AS.110.212).
Prerequisites: Students may receive credit for EN.550.426/EN.553.426 or
EN.553.626, but not both.
Instructor(s): J. Wierman
Area: Engineering, Quantitative and Mathematical Sciences.

EN.553.630. Introduction to Statistics. 4.0 Credits.
Introduction to the basic principles of statistical reasoning and data
analysis. Emphasis on techniques of application. Classical parametric
estimation, hypothesis testing, and multiple decision problems; linear
models, analysis of variance, and regression; nonparametric and robust
procedures; decision-theoretic setting, Bayesian methods. Recommended
Course Background: EN.553.620 AND ( AS.110.201 OR AS.110.212 OR
EN.553.291 ).
Prerequisites: Students may receive credit for EN.550.430/EN.553.430 or
EN.553.630, but not both.
Instructor(s): D. Athreya
Area: Engineering, Quantitative and Mathematical Sciences.
**EN.553.633. Monte Carlo Methods. 4.0 Credits.**
The objective of the course is to survey essential simulation techniques for popular stochastic models. The stochastic models may include classical time-series models, Markov chains and diffusion models. The basic simulation techniques covered will be useful in sample-generation of random variables, vectors and stochastic processes, and as advanced techniques, importance sampling, particle filtering and Bayesian computation may be discussed. Recommended Course Background: EN.553.630.

**Prerequisites:** Students may receive credit for EN.550.433/EN.553.433 or EN.553.633, but not both.

Instructor(s): J. Spall
Area: Engineering, Quantitative and Mathematical Sciences.

**EN.553.636. Data Mining. 4.0 Credits.**
Data mining is a relatively new term used in the academic and business world, often associated with the development and quantitative analysis of very large databases. Its definition covers a wide spectrum of analytic and information technology topics, such as machine learning, artificial intelligence, statistical modeling, and efficient database development. This course will review these broad topics, and cover specific analytic and modeling techniques such as advanced data visualization, decision trees, neural networks, nearest neighbor, clustering, logistic regression, and association rules. Although some of the mathematics underlying these techniques will be discussed, our focus will be on the application of the techniques to real data and the interpretation of results. Because use of the computer is extremely important when "mining" large amounts of data, we will make substantial use of data mining software tools to learn the techniques and analyze datasets. Recommended Course Background: (AS.110.202 OR AS.110.211) AND (AS.110.201 OR AS.110.212) OR EN.553.291.

**Prerequisites:** Students may receive credit for EN.550.436/EN.553.436 or EN.553.636, but not both.

Instructor(s): T. Budavari
Area: Engineering, Quantitative and Mathematical Sciences.

**EN.553.639. Time Series Analysis. 3.0 Credits.**
Time series analysis from the frequency and time domain approaches. Descriptive techniques; regression analysis; trends, smoothing, prediction; linear systems; serial correlation; stationary processes; spectral analysis. Recommended course background: EN.553.620 and (AS.110.201 OR AS.110.212 OR EN.553.291).

**Prerequisites:** Students may receive credit for EN.550.439/EN.553.439 or EN.553.639, but not both.

Instructor(s): D. Naiman, F. Torcaso, M. Pemy
Area: Engineering, Quantitative and Mathematical Sciences.

**EN.553.641. Equity Markets and Quantitative Trading. 3.0 Credits.**
This course introduces equity markets from a mathematical point of view. The properties of equities and equity-linked instruments will be described. Several quantitative trading strategies will be studied. Order execution tactics and the effect of market structure will be analyzed. Students will select a specialized aspect of the equity markets to investigate and complete a related independent project. Recommended Course Background: EN.553.642 OR EN.553.644 OR Instructor's Permission.

**Prerequisites:** Students may receive credit for EN.550.441/EN.553.441 or EN.553.641, but not both.

Instructor(s): J. Miller
Area: Engineering, Quantitative and Mathematical Sciences.

**EN.553.642. Investment Science. 4.0 Credits.**
This course offers a rigorous treatment of the subject of investment as a scientific discipline. Mathematics is employed as the main tool to convey the principles of investment science and their use to make investment calculations for good decision-making. Topics covered in the course include the basic theory of interest and its application to fixed-income securities, cash flow analysis and capital budgeting, mean-variance portfolio theory, and the associated capital asset pricing model, utility function theory and risk analysis, derivative securities and basic option theory, portfolio evaluation. The student is expected to be comfortable with the use of mathematics as a method of deduction and problem solving. Recommended Course Background: (AS.110.107 OR AS.110.109 OR AS.110.113) AND (EN.553.291 OR AS.110.201 OR AS.110.212) AND (EN.553.310 OR EN.553.311 OR EN.553.420 OR EN.553.430).

**Prerequisites:** Students may receive credit for EN.550.442 or EN.550.442/EN.553.442 or EN.553.642, but not both.

Instructor(s): J. Miller
Area: Engineering, Quantitative and Mathematical Sciences.

**EN.553.644. Introduction to Financial Derivatives. 4.0 Credits.**
This course will develop the mathematical concepts and techniques for modeling cash instruments and their hybrids and derivatives. Recommended Course Background: AS.110.302 AND EN.553.620.

**Prerequisites:** Students may receive credit for EN.550.444/EN.553.444 or EN.553.644, but not both.

Instructor(s): D. Audley
Area: Engineering, Quantitative and Mathematical Sciences.

**EN.553.645. Interest Rate and Credit Derivatives. 4.0 Credits.**
Advances in corporate finance, investment practice and the capital markets have been driven by the development of a mathematically rigorous theory for financial instruments and the markets in which they trade. This course builds on the concepts, techniques, instruments and markets introduced in EN.553.644. In addition to new topics in credit enhancement and structured securities, the focus is expanded to include applications in portfolio theory and risk management, and covers some numerical and computational approaches. Recommended Course Background: EN.553.644

**Prerequisites:** Students may receive credit for EN.550.445/EN.553.445 or EN.553.645, but not both.

Instructor(s): D. Audley
Area: Engineering, Quantitative and Mathematical Sciences.

**EN.553.646. Risk Measurement/Management in Financial Markets. 4.0 Credits.**
This course applies advanced mathematical techniques to the measurement, analysis, and management of risk. The focus is on financial risk. Sources of risk for financial instruments (e.g., market risk, interest rate risk, credit risk) are analyzed; models for these risk factors are studied and the limitation, shortcomings and compensatory techniques are addressed. Recommended Course Background: EN.553.644.

**Prerequisites:** Students may receive credit for EN.550.446/EN.553.446 or EN.553.646, but not both.

Instructor(s): D. Audley
Area: Engineering, Quantitative and Mathematical Sciences.
EN.553.647. Quantitative Portfolio Theory and Performance Analysis. 4.0 Credits.
This course focuses on modern quantitative portfolio theory, models, and analysis. Topics include intertemporal approaches to modeling and optimizing asset selection and asset allocation; benchmarks (indexes), performance assessment (including, Sharpe, Treynor and Jensen ratios) and performance attribution; immunization theorems; alpha-beta separation in management, performance measurement and attribution; Replicating Benchmark Index (RBI) strategies using cash securities / derivatives; Liability-Driven Investment (LDI); and the taxonomy and techniques of strategies for traditional management: Passive, Quasi-Passive (Indexing) Semi-Active (Immunization & Dedicated) Active (Scenario, Relative Value, Total Return and Optimization). In addition, risk management and hedging techniques are also addressed.
Prerequisites: Students may receive credit for (EN.550.447 OR EN.553.447) OR EN.553.647, but not both.
Instructor(s): D. Audley
Area: Engineering, Quantitative and Mathematical Sciences.

EN.553.649. Advanced Equity Derivatives. 4.0 Credits.
This course will cover the pricing, trading and risk management of equity derivatives, with emphasis on more exotic derivatives such as path-dependent and multi-asset derivatives. The course will emphasize practical issues: students will build their own pricing and risk management tools, and gain experience simulating the dynamic hedging of a complex derivatives portfolio. Students will practice structuring and selling equity derivative products. Pricing issues such as model selection, unobservable input parameters and calibration will be discussed, and students will learn techniques to manage the often highly nonlinear and discontinuous risks associated with these products. The course will have a significant computing component: both in the classroom and as homework projects, students will use Excel, write VBA macros and write and call C++ routines in the Microsoft Windows environment (which is the most common computing environment used by the financial industry).
Recommended Course Background: EN.553.444.
Prerequisites: Students may receive credit for EN.550.449/EN.553.449 or EN.553.649, but not both.
Instructor(s): J. Miller
Area: Engineering, Quantitative and Mathematical Sciences.

EN.553.650. Computational Molecular Medicine. 4.0 Credits.
Computational systems biology has emerged as the dominant framework for analyzing high-dimensional "omics" data in order to uncover the relationships among molecules, networks and disease. In particular, many of the core methodologies are based on statistical modeling, including machine learning, stochastic processes and statistical inference. We will cover the key aspects of this methodology, including measuring associations, testing multiple hypotheses, and learning predictors, Markov chains and graphical models. In addition, by studying recent important articles in cancer systems biology, we will illustrate how this approach enhances our ability to annotate genomes, discover molecular disease networks, detect disease, predict clinical outcomes, and characterize disease progression. Whereas a good foundation in probability and statistics is necessary, no prior exposure to molecular biology is required (although helpful). Recommended Course Background: EN.553.620 AND EN.553.630.
Prerequisites: Students may receive credit for EN.550.450/EN.553.450 or EN.553.650, but not both.
Instructor(s): D. Geman
Area: Engineering, Quantitative and Mathematical Sciences.

EN.553.653. Mathematical Game Theory. 4.0 Credits.
Mathematical analysis of cooperative and noncooperative games. Theory and solution methods for matrix game (two players, zero-sum payoffs, finite strategy sets), games with a continuum of strategies, N-player games, games in rule-defined form. The roles of information and memory. Selected applications to economic, recreational, and military situations.
Prereq: Multivariable Calculus, probability, linear algebra. Recommended Course Background: (AS.110.202 OR AS.110.211) AND EN.553.620 AND (EN.553.291 OR AS.110.201 OR AS.110.212)
Prerequisites: Students may receive credit for EN.550.453/EN.553.453 or EN.553.653, but not both.
Instructor(s): B. Castello
Area: Engineering, Quantitative and Mathematical Sciences.

EN.553.661. Optimization in Finance. 4.0 Credits.
A survey of many of the more important optimization methods and tools that are found to be useful in financial applications. Recommended Course Background: EN.553.642 OR EN.553.644.
Prerequisites: Students may receive credit for EN.550.451/EN.553.451 or EN.553.661, but not both.
Instructor(s): B. Castello
Area: Engineering, Quantitative and Mathematical Sciences.

EN.553.663. Network Models in Operations Research. 4.0 Credits.
In-depth mathematical study of network flow models in operations research, with emphasis on combinatorial approaches for solving them. Introduction to techniques for constructing efficient algorithms, and to some related data structures, used in solving shortest-path, maximum-volume, flow, and minimum-cost flow problems. Emphasis on linear models and flows, with brief discussion of non-linear models and network design. Recommended Course Background: EN.553.361 OR EN.553.761 OR EN.553.661.
Prerequisites: Students may receive credit for EN.550.463/EN.553.463 or EN.553.663, but not both.
Instructor(s): B. Castello
Area: Engineering, Quantitative and Mathematical Sciences.

EN.553.665. Introduction to Convexity. 4.0 Credits.
Convexity is a simple mathematical concept that has become central in a diverse range of applications in engineering, science and business applications. Our main focus from the applications perspective will be the use of convexity within optimization problems, where convexity plays a key role in identifying the "easy" problems from the "hard" ones. The course will have an equal emphasis on expositing the rich mathematical structure of the field itself (properties of convex sets, convex functions, Helly-Carathéodory-Radon type theorems, polarity/duality, subdifferential calculus, polyhedral theory), and demonstrating how these ideas can be leveraged to model and solve optimization problems (via a detailed study of linear programming and basics of nonlinear convex optimization).
Recommended Course Background: Familiarity with basic real analysis, linear algebra.
Prerequisites: Students may receive credit for EN.550.465/EN.553.465 or EN.553.665, but not both.
Instructor(s): A. Basu.
EN.553.671. Combinatorial Analysis. 4.0 Credits.
An introduction to combinatorial analysis at the graduate level. Meets concurrently with 553.471. Counting techniques: generating functions, recurrence relations, Polya's theorem. Combinatorial designs: Latin squares, finite geometries, balanced incomplete block designs. Emphasis on problem solving. Recommended Course Background: EN.553.291 or AS.110.201
Prerequisites: Students may receive credit for EN.550.471/EN.553.471 or EN.553.671, but not both.
Instructor(s): E. Gnang.

EN.553.672. Graph Theory. 4.0 Credits.
Study of systems of “vertices” with some pairs joined by “edges.” Theory of adjacency, connectivity, traversability, feedback, and other concepts underlying properties important in engineering and the sciences. Topics include paths, cycles, and trees; routing problems associated with Euler and Hamilton; design of graphs realizing specified incidence conditions and other constraints. Attention directed toward problem solving, algorithms, and applications. One or more topics taken up in greater depth. Recommended Course Background: (EN.553.291 OR AS.110.201 OR AS.110.212)
Prerequisites: EN.550.291 OR AS.110.201 OR AS.110.212; Students may receive credit for EN.550.472/EN.553.472 or EN.553.672, but not both.
Instructor(s): E. Gnang.

EN.553.673. Introduction to Nonlinear Dynamics and Chaos. 3.0 Credits.
An introduction to the phenomenology of nonlinear dynamic behavior with emphasis on models of actual physical, chemical, and biological systems, involving an interdisciplinary approach to ideas from mathematics, computing, and modeling. The common features of the development of chaotic behavior in both mathematical models and experimental studies are stressed, and the use of modern data-mining tools to analyze dynamic data will be explored. Some computing experience is desirable. Emphasis will be placed on the geometric/visual computer-aided description and understanding of dynamics and chaos. Recommended course background: [(AS.110.201 or AS.110.212) and (AS.110.302 or AS.110.306)] or EN.553.291.
Prerequisites: Students may receive credit for only one of EN.553.473 OR EN.553.673 OR EN.540.468 OR EN.540.668.; [(AS.110.201 OR AS.110.212) AND (AS.110.302 OR AS.110.306)] OR EN.553.291
Instructor(s): Y. Kevrekidis.

EN.553.685. Introduction to Harmonic Analysis and Its Applications. 4.0 Credits.
The course is an introduction to methods in harmonic analysis, in particular Fourier series, Fourier integrals, and wavelets. These methods will be introduced rigorously, together with their motivations and applications to the analysis of basic partial differential equations and integral kernels, signal processing, inverse problems, and statistical/machine. Recommended Course Background: (AS.110.201 OR AS.110.212 OR EN.553.291) AND (AS.110.202 OR AS.110.211) AND (AS.110.405 OR AS.110.415)
Prerequisites: Students may receive credit for only one of the following: AS.110.433, EN.553.485, or EN.553.685.
Instructor(s): M. Maggioni.

EN.553.688. Financial Computing I. 3.0 Credits.
This course is aimed for student who need to develop the ability to use programming languages to solve data analytic problems that are likely to arise in financial applications. The C programming language will be introduced, and students will be exposed to some of the more useful C++ enhancements. The Python language will be introduced as well. Recommended Course Background: EN.553.310 OR EN.553.311 OR (EN.553.420 AND EN.553.430). Students should be comfortable using computers but no prior programming background is required. Some finance background is helpful but not necessary.
Prerequisites: Students may receive credit for EN.553.488 or EN.553.688, but not both.
Instructor(s): E. Gnang.

EN.553.692. Mathematical Biology. 3.0 Credits.
This course will examine the mathematical methods relevant to modeling biological phenomena, particularly dynamical systems and probability. Topics include ordinary differential equations and their simulation; stability and phase plane analysis; branching processes; Markov chains; and stochastically perturbed systems. Biological applications will be drawn from population growth, predator-prey dynamics, epidemiology, genetics, intracellular transport, and neuroscience. Recommended Course Background: EN.553.620 AND (AS.110.201 OR AS.110.212) AND (AS.110.302 OR AS.110.306 OR EN.553.291)
Prerequisites: Students may receive credit for EN.550.492/EN.553.492 or EN.553.692, but not both.
Instructor(s): D. Athreya
Area: Natural Sciences, Quantitative and Mathematical Sciences.

EN.553.693. Mathematical Image Analysis. 3.0 Credits.
This course gives an overview of various mathematical methods related to several problems encountered in image processing and analysis, and presents numerical schemes to address them. It will focus on problems like image denoising and deblurring, contrast enhancement, segmentation and registration. The different mathematical concepts shall be introduced during the course; they include in particular functional spaces such as Sobolev and BV, Fourier and wavelet transforms, as well as some notions from convex optimization and numerical analysis. Most of such methods will be illustrated with algorithms and simulations on discrete images, using MATLAB. Prerequisites: linear algebra, multivariate calculus, basic programming in MATLAB. Recommended Course Background: (AS.110.202 OR AS.110.211) AND (EN.553.291 OR AS.110.201 OR AS.110.212)
Prerequisites: Students may receive credit for EN.550.493/EN.553.493 or EN.553.693, but not both.
Instructor(s): P. Escande
Area: Engineering, Quantitative and Mathematical Sciences.

EN.553.694. Applied and Computational Linear Algebra. 3.0 Credits.
In this seminar we plan to discuss generalizations of theorems and algorithms from matrix theory to hypermatrices. More specifically the seminar will discuss hypermatrix/tensor algebras, rank, spectra and transforms. Using the python friendly free open-source mathematics software SageMath and the hypermatrix algebra package we will discuss applications of hypermatrices to combinatorics, machine learning and data analysis. Preliminary knowledge of the Python language is not required. Recommended Course Background: AS.110.212 OR AS.110.201 OR EN.553.291.
Prerequisites: Students may receive credit for EN.553.494 or EN.553.694, but not both.
Instructor(s): E. Gnang.
EN.553.700. Master's Research. 3.0 - 10.0 Credits.
Reading, research, or project work for Master's level students. Arranged individually between students and faculty.
Instructor(s): Staff.

EN.553.701. Real Analysis: Preparation for the Ph.D. Introductory Examination. 4.0 Credits.
This course is designed to prepare students for the Real Analysis part of the introductory exam of the Department of Applied Mathematics and Statistics. In this course we will cover fundamental topics in real analysis, such as, Set Theory, The Topology of Euclidean Space, Continuous Mappings, Uniform Convergence, Differentiable Mappings, Inverse & Implicit Function Theorems, Integration Theory, Fourier Series, and Basics of Differential Equations.
Instructor(s): N. Charon.

EN.553.720. Probability Theory I. 4.0 Credits.
The course objectives are to develop probabilistic reasoning and problem solving approaches, to provide a rigorous mathematical basis for probability theory, and to examine several important results in the theory of probability. Topics include axiomatic probability, independence, random variables and their distributions, expectation, integration, variance and moments, probability inequalities, and modes of convergence of random variables. The course will include introductory measure theory as needed. Students are expected to have previous study of both analysis and probability. This course is the first half of a yearlong sequence. The second semester’s course, EN.553.721 Probability Theory II, will cover classical limit theorems, characteristic functions, and conditional expectation.
Prerequisites: Students may take EN.550.620 or EN.553.720, but not both.
Instructor(s): J. Fill.

EN.553.721. Probability Theory II. 4.0 Credits.
Probability at the level of measure theory, focusing on limit theory. Modes of convergence, Poisson convergence, three-series theorem, strong law of large numbers, continuity theorem, central limit theorem, Berry-Esseen theorem, infinitely divisible and stable laws. Recommended Course Background: EN.553.720 AND (AS.110.405 OR AS.110.415)
Instructor(s): J. Fill.

EN.553.722. Introduction to Stochastic Calculus. 3.0 Credits.
A graduate-level class on stochastic calculus, providing a rigorous introduction on stochastic integrals and differential equations.
Prerequisites: EN.550.621[C]
Instructor(s): M. Bichuch.

EN.553.723. Markov Chains. 3.0 Credits.
Recent advances in computer science, physics, and statistics have been made possible by corresponding sharply quantitative developments in the mathematical theory of Markov chains. Possible topics: rates of convergence to stationarity, eigenvalue techniques, Markov chain Monte Carlo, perfect simulation, self-organizing data structures, approximate counting and other applications to computer science, reversible chains, interacting particle systems. This course will be graded pass/fail.
Instructor(s): J. Fill.

EN.553.727. Large Deviations Theory. 3.0 Credits.
This course presents an introduction to the theory of large deviations, which provides a quantitative framework for understanding exponentially rare events. Topics encompass the development of large deviation principles in both finite and infinite-dimensional settings, from empirical measures of i.i.d samples to random perturbations of dynamical systems. Applications include problems in information theory, hypothesis testing, and transitions between steady states in biological and physical models.
Instructor(s): D. Athreya.

EN.553.730. Statistical Theory. 4.0 Credits.
The fundamentals of mathematical statistics will be covered. Topics include: distribution theory for statistics of normal samples, exponential statistical models, the sufficiency principle, least squares estimation, maximum likelihood estimation, uniform minimum variance unbiased estimation, hypothesis testing, the Neyman-Pearson lemma, likelihood ratio procedures, the general linear model, the Gauss-Markov theorem, simultaneous inference, decision theory, Bayes and minimax procedures, chi-square methods, goodness-of-fit tests, and nonparametric and robust methods.
Prerequisites: Students may take EN.550.630 or EN.553.730, but not both.
Instructor(s): C. Priebe.

EN.553.731. Statistical Theory II. 3.0 Credits.
Advanced concepts and tools fundamental to research in mathematical statistics and statistical inference: asymptotic theory, optimality, various mathematical foundations.
Instructor(s): D. Naiman.

EN.553.732. Bayesian Statistics. 3.0 Credits.
The course will cover Bayesian methods for exploratory data analysis. The emphasis will be on applied data analysis in various disciplines. We will consider a variety of topics, including introduction to Bayesian inference, prior and posterior distribution, hierarchical models, spatial models, longitudinal models, models for categorical data and missing data, model checking and selection, computational methods by Markov Chain Monte Carlo using R or Matlab. We will also cover some nonparametric Bayesian models if time allows, such as Gaussian processes and Dirichlet processes. Prerequisite: 553.730 (recommended) or 553.630
Prerequisites: Students may take EN.550.632 or EN.553.732, but not both.
Instructor(s): Y. Xu.

EN.553.733. Advanced Topics in Bayesian Statistics. 3.0 Credits.
This course covers advanced topics in Bayesian statistical analysis beyond the introductory course. Therefore knowledge of basic Bayesian statistics is assumed (at the level of “A first course in Bayesian statistical methods”, by Peter Hoff (Springer, 2009). The models and computational methods will be introduced with emphasis on applications to real data problems. This course will cover nonparametric Bayesian models including Gaussian process, Dirichlet process (DP), Polya trees, dependent DP, Indian buffet process, etc. Recommended Course Background: EN.553.732 or permission from the instructor
Instructor(s): Y. Xu.
EN.553.734. Introduction to Nonparametric Estimation. 3.0 Credits.
This course will cover the fundamental topics in the theory of nonparametric estimation. Several different nonparametric estimators (e.g., kernel, local polynomial, projection, spline, and trigonometric) and their statistical properties will be considered. Minimax lower bounds for a variety of nonparametric estimation problems will be discussed. A number of topics related to estimator asymptotic efficiency and adaptation will be studied. An overview of shape constrained nonparametric estimation will be presented for a variety of shape constraints (e.g., monotonicity and convexity).
Prerequisites: EN.550.630
Instructor(s): T. Lebair.

EN.553.735. Topics in Statistical Pattern Recognition. 3.0 Credits.
The Dissimilarity Representation for Pattern Recognition. This course will investigate aspects of statistical inference and statistical pattern recognition associated with observing only dissimilarities between entities rather than observing feature vectors associated with the individual entities themselves.
Instructor(s): C. Priebe.

EN.553.736. System Identification and Likelihood Methods. 2.0 Credits.
The focus of this roundtable-format course will be stochastic modeling as relates to system identification and maximum likelihood. The principles and algorithms being covered in this course have tremendous importance in the world at large. For example, maximum likelihood is arguably the most popular method for parameter estimation in most real-world applications. System identification is the term used in many fields to refer to the process of mathematical model building from experimental data, with a special focus on dynamical systems. The system identification process refers to several important aspects of model building, including selection of the model form (linear or nonlinear, static or dynamic, etc.), experimental design, parameter estimation, and model validation. This course will cover topics such as the maximum likelihood formulation and theory for dynamical systems, the EM (expectation-maximization) algorithm and its variants, Fisher information, common model structures, online versus offline estimation, the role of feedback in identification (i.e., open-loop versus closed-loop estimation), standard and extended Kalman filtering, and uncertainty characterization (e.g., confidence regions).
Recommended Course Background: Undergraduate-level matrix theory and ordinary differential equations; graduate-level course in probability and statistics (e.g., 553.430 or equivalent; in particular, students should have prior exposure to maximum likelihood and Bayes’ rule). Prior experience in data analysis and algorithms will be helpful.
Instructor(s): J. Spall.

EN.553.737. Distribution-free statistics and Resampling Methods. 3.0 Credits.
Distribution-free and resampling methods address statistical estimation, testing and validation under minimal assumptions on the true distribution of observed data, avoiding, in particular, to rely on some specific parametric class (e.g., Gaussian). The course will study the following topics: order statistics, rank-based methods, tests of independence, symmetry, location differences, scale differences and goodness-of-fit, permutation tests and bootstrap with an introduction to the problem of multiple comparisons. Recommended Courses: EN.553.430 or EN.553.730 or equivalent.
Instructor(s): E. Younes.

EN.553.738. High-Dimensional Approximation, Probability, and Statistical Learning. 3.0 Credits.
The course covers fundamental mathematical ideas for certain approximation and statistical learning problems in high dimensions. We start with basic approximation theory in low-dimensions, in particular linear and nonlinear approximation by Fourier and wavelets in classical smoothness spaces, and discuss applications in imaging, inverse problems and PDE’s. We then introduce notions of complexity of function spaces, which will be important in statistical learning. We then move to basic problems in statistical learning, such as regression and density estimation. The interplay between randomness and approximation theory is introduced, as well as fundamental tools such as concentration inequalities, basic random matrix theory, and various estimators are constructed in detail, in particular multi scale estimators. At all times we consider the geometric aspects and interpretations, and will discuss concentration of measure phenomena, embedding of metric spaces, optimal transportation distances, and their applications to problems in machine learning such as manifold learning and dictionary learning for signal processing.
Instructor(s): M. Maggioni.

EN.553.739. Statistical Pattern Recognition Theory & Methods. 3.0 Credits.
This biennial course covers topics in the theory, methods, and applications of machine learning from an explicitly statistical perspective. Recommended Course Background: (EN.550.420 OR EN.553.420 OR EN.553.620) AND (EN.550.430 OR EN.553.430 OR EN.553.630)
Instructor(s): C. Priebe.

EN.553.740. Machine Learning. 3.0 Credits.
This course will focus on theoretical and practical aspects of statistical learning. We will review of a collection of learning algorithms for classification and regression estimation, including linear methods, kernel methods, tree-based and boosting methods; we will also discuss unsupervised methods for linear and nonlinear data reduction and clustering. We will introduce fundamental concepts of the theory of model selection and validation: bias/variance dilemma, penalty methods, and some measures of complexity; the course will also describe standard validation algorithms, like cross-validation and bootstrap. Recommended prerequisite: 553.620 and 553.630.
Instructor(s): E. Younes.

EN.553.742. Statistical Inference on Graphs. 3.0 Credits.
This course provides an introduction to and overview of current research in random graph inference, with a particular focus on spectral methods and their applications to inference for independent-edge random graphs. Topics include concentration inequalities; analysis of matrix perturbations; spectral decompositions of graph adjacency and Laplacian matrices; consistent estimation of latent variables associated to vertices; clustering, community detection, and classification in networks; and multi-sample hypothesis testing for graphs. Emphasis will be on a framework for establishing classical properties—consistency, normality, and efficiency—for estimators of graph parameters. Students will read papers in the literature and are expected to participate actively in class. Recommended prerequisites EN.553.792 and EN.553.630.
Instructor(s): D. Athreya; M. Tang.
EN.553.743. Graphical Models. 4.0 Credits.
This course describes how models based on networks encoding the conditional dependency structure between random variables, also called graphical models, can be used to design multivariate probability distributions. A special focus will be made on important particular cases, like Markov Chains, Bayesian networks or Markov Random Fields. We will also discuss parametric estimation and inference problems, and issues arising when some of the variables cannot be observed.
Prerequisites: EN.550.420 or equivalent AND EN.550.430 or equivalent
Instructor(s): Staff.

EN.553.746. Advanced Topics in Derivatives. 1.0 Credit.
Topics will include static arbitrage versus dynamic arbitrage, proof of Black-Scholes formula using a change of measure, the Modigliani-Miller representation of the corporation, Merton model of corporate debt valuation, Asian options’ operational use, pricing and hedging, stochastic volatility and local volatility models; elements of market microstructure and high frequency trading. Grading will be mostly based on oral presentations. The course is aimed at second year Master’s students and will not begin meetings until mid-October.
Instructor(s): H. Geman.

EN.553.749. Advanced Financial Theory. 3.0 Credits.
The first part of the course will review in depth the main instruments in the various asset classes, as well as the founding results on investment decision, capital budgeting and project financing. The second part will analyze the theory of the firm: capital structure, dilution and share repurchase, dividend policy, Modigliani-Miller theorem and will lead to the contingent claim pricing of corporate debt and equity as in Merton (1974) and its extensions. The third part will extend the CAPM to the Arbitrage Pricing Theory of Ross (1976) and its theoretical and operational consequences. The fourth part will be dedicated to the stochastic modelling of the yield curve to price caps, floors and swaptions, and their use in the Asset Liability Management of a bank and insurance company. This course will not begin until mid-October.
Prerequisites: Students may take EN.550.649 or EN.553.749, but not both.
Instructor(s): H. Geman.

EN.553.753. Commodities and Commodity Markets. 4.0 Credits.
The first half of this course will be devoted to energy markets, both in terms of the market itself and how to model peculiar features of this business. First we will discuss fossil fuels, including physical and financial natural gas and LNG; crude and refined petroleum commodities; and possibly coal markets. Then the focus will turn to electricity markets, including market structures; energy, capacity and ancillary services markets; characteristics of demand; power plant commitment and dispatch; the “stack” or market supply curve; characteristics of different plants and fuels; regional differences in markets; and hedging techniques from trading vanilla products all the way to complex multi-commodity structures. We will discuss renewable energy sources, their characteristics, economics, and effects on the larger market, as well as emissions markets as a way of removing pollution externalities. The first half will conclude by elaborating on risk management techniques; credit; legislation and regulation; and derivative accounting as time permits. The second half of the course will turn to shipping, metals and agricultural markets. The metal physical markets will be described, the major Exchanges presented (LME, SHFE), as well as the warehousing issues in the case of base metals. The case of precious metals will be singled out, and gold in particular; and finally uranium and rare earths. Agricultural (grains and softs) markets will be presented, together with the crucial issues of biofuels, fertilizers, water, and arable land. In all cases, there will be a large focus on the trading activities – both to hedge and to gain exposure to commodities – in spot and derivative markets. Numerous examples of forward curves will be provided, as well as volatility skews. The valuation of swaps, spread options and Asian options will be (re)derived. Students should have rudimentary knowledge of financial markets. Recommended Course Background: EN.553.620 and AS.110.106 or AS.110.108
Instructor(s): G. Schultz; H. Geman.

EN.553.761. Nonlinear Optimization I. 3.0 Credits.
This course considers algorithms for solving various nonlinear optimization problems and, in parallel, develops the supporting theory. The primary focus will be on unconstrained optimization problems.
Topics for the course will include: necessary and sufficient optimality conditions; steepest descent method; Newton and quasi-Newton based line-search, trust-region, and adaptive cubic regularization methods; linear and nonlinear least-squares problems; linear and nonlinear conjugate gradient methods. Recommended Course Background: Multivariable Calculus, Linear Algebra, Real Analysis such as AS.110.405
Prerequisites: Students may take EN.550.661 or EN.553.761, but not both.
Instructor(s): A. Basu.

EN.553.762. Nonlinear Optimization II. 3.0 Credits.
This course considers algorithms for solving various nonlinear optimization problems and, in parallel, develops the supporting theory. The primary focus will be on constrained optimization problems. Topics for the course will include: necessary and sufficient optimality conditions for constrained optimization; projected-gradient and two-phase accelerated subspace methods for bound-constrained optimization; simplex and interior-point methods for linear programming; duality theory; and penalty, augmented Lagrangian, sequential quadratic programming, and interior-point methods for general nonlinear programming. In addition, we will consider the Alternating Direction Method of Multipliers (ADMM), which is applicable to a huge range of problems including sparse inverse covariance estimation, consensus, and compressed sensing. Recommended Course Background: Multivariable Calculus, Linear Algebra, Real Analysis such as AS.110.405.
Instructor(s): D. Robinson.
EN.553.760. Combinatorial Optimization. 3.0 Credits.
The main goal of this course is to introduce students to combinatorial optimization techniques. The first part of the course will focus on combinatorial algorithms for classical problems. The next part of the course will show how polyhedral theory can be used to deal with combinatorial optimization problems in a unifying manner. Familiarity with linear programming and algorithms desirable but not strictly required. Recommended Course Background: Linear Algebra.
Instructor(s): A. Basu.

EN.553.769. Topics in Discrete Optimization. 3.0 Credits.
We will study solution techniques for problems in discrete optimization, emphasizing computational aspects of the theory and algorithms. Recommended Prerequisites: good backgrounds in linear programming and graph theory.
Instructor(s): W. Cook.

EN.553.770. Topics in Discrete Math. 3.0 Credits.
Topics in Discrete Mathematics: Graphons. Just as real numbers can be defined as limits of convergent sequences of rational numbers, graphons are the limits of convergent sequences of graphs. The notion of a graphon is very recent (less than a decade old) but graphons already are playing an interesting role in pure combinatorics (extremal graph problems) and in applications/algorithms for huge networks. Active participation by students is key as we work our way through challenging ideas.
Instructor(s): E. Scheinerman.
EN.553.784. Mathematical Foundations of Computational Anatomy. 3.0 Credits.
The course will provide fundamental concepts and methods that pertain the analysis of the variation of anatomical shapes extracted from medical images. It will review basic properties of the most important shape representations (landmark, curves, surfaces, images...), describe distances and discrepancy measures that allow for their comparison, and introduce nonlinear optimal control methods that underlie the Large Deformation Diffeomorphic Metric Mapping (LDDMM) family of registration algorithms. The course will then discuss shape averaging methods and template-centered representations for the analysis of shape datasets. Recommended Course Background: Optimization (EN.553.361 or higher) and (AS.110.202 OR AS.110.211 or higher) AND AS.110.302 or higher.
Instructor(s): E. Younes.

EN.553.790. Neural Networks and Feedback Control Systems. 2.0 Credits.
This roundtable course is an introduction to two related areas?neural networks (NNs) and control systems based on the use of feedback. Artificial NNs are effective conceptual and computational vehicles for many important applications; feedback control is relevant to virtually all natural and human-made systems. NNs are applied in areas such as system modeling and control, function approximation, time-series filtering/prediction/smoothing, speech/image/signal processing, and pattern recognition. Topics to be covered for NNs include network architecture, learning algorithms, and applications. Specific NNs discussed include perceptrons, feedforward networks with backpropagation, and recurrent networks. This course also provides an introduction to feedback control systems, including the role of feedback in regulating systems and in achieving stability in systems. We consider stochastic (noise) effects in feedback systems. We also consider the interface of NNs and control by discussing how NNs are used in building modern control systems in problems where standard methods are infeasible. Recommended Course Background: Matrix theory, differential equations, and a graduate course in probability and statistics.
Instructor(s): J. Spall.

EN.553.791. Financial Mathematics Master's Summer Internship. 2.0 Credits.
This course is open only to AMS department master’s students.
Instructor(s): D. Audley; D. Naiman; J. Miller; M. Bichuch.

EN.553.792. Matrix Analysis and Linear Algebra. 4.0 Credits.
A second course in linear algebra with emphasis on topics useful in analysis, economics, statistics, control theory, and numerical analysis. Review of linear algebra, decomposition and factorization theorems, positive definite matrices, norms and convergence, eigenvalue location theorems, variational methods, positive and nonnegative matrices, generalized inverses.
Prerequisites: Students may take EN.550.692 or EN.553.792, but not both.
Instructor(s): D. Fishkind.

EN.553.793. Turbulence Theory. 3.0 Credits.
An advanced introduction to turbulence theory for graduate students in the physical sciences, engineering and mathematics. Both intuitive understanding and exact analysis of the fluid equations will be stressed. Previous familiarity with fluid mechanics is not required, although it could be helpful.
Instructor(s): G. Eyink.

EN.553.795. Advanced Parameterization in Science and Engineering. 3.0 Credits.
This course will present an overview of topics in science-based parameterization, including dynamics, probability and other applied mathematical methods. These concepts will be presented in a unified format, with some emphasis on scientific computing. Specific topics include: basic probability, statistical dynamics, (moment hierarchies, Liouville/forward equations, path-integral methods), asymptotic closure (homogenization, Chapman-Enskog), closure techniques without any separation of scales (non-linear Galerkin & Weighted residuals, algebraic closures, PDF-based closures, down-scaling), uncertainty quantification (variance & other measures of uncertainty, Bayesian estimation, ensemble methods), hybrid methods.
Instructor(s): G. Eyink
Area: Engineering, Quantitative and Mathematical Sciences.

EN.553.797. Introduction to Control Theory and Optimal Control. 3.0 Credits.
A control system is a dynamical system on which one can act through a parameter that can be chosen freely at any point in time. In this class, we will be interested in two main problems. The first one is controllability, which studies conditions for the existence of controls allowing an initial point to be driven to any other point. The second one is optimal control, in which we will study methods to minimize a certain cost over all possible controls, possibly with endpoint constraints. Such problems have many applications in engineering: crossing a river with minimal fuel, planning trajectories of rocket engines etc. Recommended Course Background: Multivariate Calculus, Linear Algebra, Differential Equations. Some familiarity with Optimization is recommended, but not mandatory.
Instructor(s): N. Charon.

EN.553.799. Topics In Applied Math. 3.0 Credits.
Analysis of Algorithms. This course in the probabilistic analysis of algorithms (AofA) will be accessible to any student who has had at least one course in probability and will be most beneficial to those who have had at least one probability course at the measure-theoretic level. The course will review basic topics from the theory of probability that have proved useful in AofA. It will provide introductions to more advanced AofA-relevant topics chosen from such topics as: Markov chains, branching processes, urn models, Poissonian (and de-Poissonian), various metrics on distributions, fixed-point characterizations of distributions, convergence of sequences of stochastic processes, perfect simulation using Markov chains (and otherwise), and large deviation principles. The course will interweave probability theory and applications to AofA, focusing on the fundamentally important and exceptionally rich example of limiting distributions for various ways of measuring the cost of executing the QuickSort and QuickSelect algorithms.
Instructor(s): J. Fill.

EN.553.800. Dissertation Research. 3.0 - 20.0 Credits.
Instructor(s): Staff.

EN.553.801. Department Seminar. 1.0 Credit.
A variety of topics discussed by speakers from within and outside the university. Required of all resident department graduate students.
Instructor(s): T. Budavari.

EN.553.802. Graduate Independent Study. 3.0 Credits.
Instructor(s): M. Maggioni.

EN.553.810. Probability & Statistics. 1.0 - 4.0 Credits.
Instructor(s): C. Priebe.

EN.553.822. Stochastic Calculus Seminar. 2.0 Credits.
Seminar and readings in stochastic calculus.
Instructor(s): M. Bichuch.
EN.553.826. Information Theory Seminar. 3.0 Credits.
Graduate seminar covering topics in information theory and information geometry. Topics may include large deviation theory, $I$-divergence, Fisher information and ergodic theory. Emphasis will be placed on developing a rigorous geometric understanding of methods and models in probability and statistics. Course cannot be counted toward AMS Master's degree requirements.  
Prerequisites: EN.550.447 OR EN.550.630 or Permission of instructor.  
Instructor(s): K. Levin.

EN.553.831. Advanced Topics in Nonparametric Bayesian Statistics. 3.0 Credits.
Will discuss advanced topics in nonparametric Bayesian statistics.  
Instructor(s): D. Audley; D. Naiman; J. Miller.

EN.553.832. Machine Learning Journal Course. 3.0 Credits.
Journal course on machine learning topics. Course is restricted to first and second year AMS PhD students, and others by permission of instructor.  
Instructor(s): D. Naiman.

EN.553.833. Bayesian Modeling in Biomedical Applications. 3.0 Credits.
This topic course will cover Bayesian modeling in biomedical applications, especially in Electronic Health Record area. The knowledge of basic Bayesian statistics (at the level of "A first course in Bayesian statistical methods" by Peter Hoff (Springer, 2009)) and Nonparametric Bayesian statistics (e.g. Gaussian process, Dirichlet process (DP), dependent DP, Indian buffet process, etc) is assumed. Students will be required to do intensive literature readings on both Bayesian modeling from statistical journals and biomedical topics from medical journals, present papers of common interests, and discuss potential research ideas for their final project.  
Instructor(s): Y. Xu.

EN.553.847. Financial Mathematics Masters Seminar. 1.0 Credit.
This course is only open to students enrolled in the MSE in Financial Mathematics program. Advanced topics chosen according to the interests of the instructor and graduate students. The course will focus on recent research articles in the financial mathematics literature.  
Instructor(s): D. Audley; D. Naiman; J. Miller.

EN.553.865. Optimization and Discrete Math. 1.0 - 4.0 Credits.
Discussion of new results in the specified research area based on journal articles, research monographs and current research. Each week a participant in the seminar will present a lecture. Organized by advanced graduate students with the sponsorship of an Applied Mathematics and Statistics faculty member.  
Instructor(s): A. Basu; D. Robinson.

EN.553.892. Matrix Analysis II Seminar. 2.0 Credits.
Continuation of EN.553.792.  
Instructor(s): N. Charon.

Cross Listed Courses
Mathematics
AS.110.795. Data Science Seminar.
Presentations of current research papers by faculty, graduate students and invited guest speakers. For graduate students only.  
Instructor(s): M. Maggioni  
Area: Quantitative and Mathematical Sciences.

General Engineering
EN.500.200. Computing for Engineers and Scientists. 4.0 Credits.
This course introduces a variety of techniques for solving problems in engineering and science on a computer using MATLAB. Topics include structure and operation of a computer, the programming language MATLAB, computational mathematics, and elementary numerical analysis. Co-listed with EN.550.200.  
Prerequisites: Prereqs: AS.110.107 OR AS.110.109
Instructor(s): J. Yoder; K. Hedrick; T. Lebair  
Area: Engineering, Quantitative and Mathematical Sciences.

Civil Engineering
EN.560.601. Applied Math for Engineers. 3.0 Credits.
This course presents a broad survey of the basic mathematical methods used in the solution of ordinary and partial differential equations: linear algebra, power series, Fourier series, separation of variables, integral transforms.  
Instructor(s): M. Zhong  
Area: Engineering, Quantitative and Mathematical Sciences.

Biomedical Engineering
EN.580.694. Statistical Connectomics. 3.0 Credits.
This course will cover the basics of an exciting emerging field of statistical connectomics (aka, brain-graphs). It is so new, that we are going to make some of it up in this class! The first week will be introductory lectures that I give. The rest of the semester will be run like a seminar; each week will focus on a different topic. On Tuesdays we will hear about a statistical method that operates on graphs, and on Thursdays we will read about some neuroscience data upon which one could apply these techniques. The final project will consist of implementing a statistical method devised for graphs on a brain-graph problem. Recommended background: coursework in probability, linear algebra, and numerical programming (eg, R, Python, Matlab).  
Instructor(s): J. Vogelstein  
Area: Engineering.

Computer Science
EN.601.442. Modern Cryptography. 3.0 Credits.
Modern Cryptography includes seemingly paradoxical notions such as communicating privately without a shared secret, proving things without leaking knowledge, and computing on encrypted data. In this challenging but rewarding course we will start from the basics of private and public key cryptography and go all the way up to advanced notions such as zero-knowledge proofs, functional encryption and program obfuscation. The class will focus on rigorous proofs and require mathematical maturity.  
[Analysis]  
Prerequisites: EN.600.271 AND (EN.553.420 or EN.553.310); Students may receive credit for only one of EN.600.442, EN.601.442, EN.601.642.  
Instructor(s): A. Jain  
Area: Engineering, Quantitative and Mathematical Sciences.
EN.601.642. Modern Cryptography. 3.0 Credits.
Same material as 601.442, for graduate students. Modern Cryptography includes seemingly paradoxical notions such as communicating privately without a shared secret, proving things without leaking knowledge, and computing on encrypted data. In this challenging but rewarding course we will start from the basics of private and public key cryptography and go all the way up to advanced notions such as zero-knowledge proofs, functional encryption and program obfuscation. The class will focus on rigorous proofs and require mathematical maturity. [Analysis] Required course background: EN.601.231 or EN.601.631.
Prerequisites: Students may receive credit for only one of EN.600.442, EN.601.442, EN.601.642.
Instructor(s): A. Jain
Area: Engineering, Quantitative and Mathematical Sciences.