Applied Mathematics and Statistics

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; and Scientific Computation, which includes all aspects of numerical computing in support of the sciences.

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 focus described below, may be obtained from the department office. Additional advisory information, including information about the areas of interest, the student should consult regularly with the faculty advisor.

In order to develop a sound program suited to individual needs and interests, the student should consult regularly with the faculty advisor. 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 (http://e-catalog.jhu.edu/undergrad-students/academic-policies/requirements-for-a-bachelors-degree), including 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
   
   AS.110.106 & AS.110.107 & AS.110.108 & AS.110.109
   Calculus I & Calculus II (For Biological and Social Science) & Calculus I & Calculus II (For Physical Sciences and Engineering)
   Calculus I & Calculus II (For Biological and Social Science) & Calculus I & Calculus II (For Physical Sciences and Engineering)
   Calculus III ((satisfies the Calculus III requirements. Advanced placement is acceptable as well))

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.

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.

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.
or AS.110.211 Honors Multivariable Calculus

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 Diff Equations/Applic
- or AS.110.417 Partial Diff Equations
- or EN.550.386 Scientific Computing: Differential Equations
- or EN.550.388 Scientific Computing: Differential Equations in Vector Spaces
- or EN.550.391 Dynamical Systems

Option B

EN.550.291 Linear Algebra and Differential Equations

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

- EN.550.385 Scientific Computing: Linear Algebra
- or EN.550.386 Scientific Computing: Differential Equations
- or EN.550.388 Scientific Computing: Differential Equations in Vector Spaces
- or EN.550.391 Dynamical Systems
- or EN.550.692 Matrix Analysis and Linear Algebra
- or AS.110.417 Partial Diff Equations


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

- AS.171.426 Practical Scientific Analysis of Big Data
- or 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.550.281 Computing in Applied Mathematics
- or EN.550.383 Scientific Computing with Python
- or EN.550.385 Scientific Computing: Linear Algebra
- or EN.550.386 Scientific Computing: Differential Equations
- or EN.550.388 Scientific Computing: Differential Equations in Vector Spaces
- or EN.550.400 Mathematical Modeling and Consulting
- or EN.550.413 Applied Statistics and Data Analysis
- or EN.550.415 Practical Scientific Analysis of Big Data
- or EN.550.427 Monte Carlo Methods
- or EN.550.430 Introduction to Statistics
- or EN.550.436 Data Mining
- or EN.550.439 Time Series Analysis
- or EN.550.443 Financial Computing in C++
- or EN.550.450 Computational Molecular Medicine
- or EN.550.487 Numerical Methods for Financial Mathematics
- or EN.550.493 Mathematical Image Analysis
- or EN.560.220 Civil Engineering Analysis
- 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.600.475 Introduction to Machine Learning

4. Discrete Mathematics

Choose one of the following:

- EN.550.171 Discrete Mathematics
- or EN.550.371 Cryptology and Coding
- or EN.550.471 Combinatorial Analysis
- or EN.550.472 Graph Theory

5. Probability and Statistics

EN.550.420 Introduction to Probability
- or EN.550.430 Introduction to Statistics

6. Optimization

EN.550.361 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 Statistics

Choose two of the following:

- AS.110.405 Analysis I
- or EN.550.400 Mathematical Modeling and Consulting
- or EN.550.413 Applied Statistics and Data Analysis
- or EN.550.426 Introduction to Stochastic Processes
- or EN.550.472 Stochastic Processes and Applications to Finance
- or EN.550.433 Monte Carlo Methods
- or EN.550.436 Data Mining
- or EN.550.439 Time Series Analysis

Scientific Computing

Choose two of the following:

- EN.550.385 Scientific Computing: Linear Algebra
- or EN.550.386 Scientific Computing: Differential Equations
- or EN.550.388 Scientific Computing: Differential Equations in Vector Spaces
- or EN.550.433 Monte Carlo Methods

Optimization and Operations Research

Choose two of the following:

- EN.550.362 Introduction to Optimization II
- or EN.550.400 Mathematical Modeling and Consulting
to students majoring in a variety of disciplines, in both the School of

The minor in applied mathematics and statistics should be attractive

Minor in Applied Mathematics and Statistics

Departmental honors. 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.

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.550.501 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.

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-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
  • (a) at least four courses in the Department of Applied Mathematics and Statistics (each of these must be a 3- or 4-credit course); and
  • (b) 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
  • (c) an approved semester course based on a high-level computer language chosen from the list below or 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).

- EN.171.426 Practical Scientific Analysis of Big Data 0-3
- or 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.550.281 Computing in Applied Mathematics
- or EN.550.383 Scientific Computing with Python
- or EN.550.385 Scientific Computing: Linear Algebra
- or EN.550.386 Scientific Computing: Differential Equations
- or EN.550.388 Scientific Computing: Differential Equations in Vector Spaces
- or EN.550.400 Mathematical Modeling and Consulting
- or EN.550.413 Applied Statistics and Data Analysis
- or EN.550.415 Practical Scientific Analysis of Big Data
- or EN.550.433 Monte Carlo Methods
- or EN.550.436 Data Mining
- or EN.550.443 Financial Computing in C++
- or EN.550.450 Computational Molecular Medicine
- or EN.550.487 Numerical Methods for Financial Mathematics
- or EN.550.493 Mathematical Image Analysis
- or EN.560.220 Civil Engineering Analysis
- 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.600.475 Introduction to Machine 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.550.310 Probability & Statistics for the Physical and Information Sciences & Engineering/EN.550.311 Probability and Statistics for the Biological Sciences and Engineering, EN.550.420 Introduction to Probability, and EN.550.430 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.

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, Geography and Environmental 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 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, or the master of science in engineering (M.S.E.) degree in financial mathematics (described in the next section). 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, the student must:

• Complete satisfactorily at least eight one-semester courses of graduate work in a coherent program approved by the faculty advisor. Some 400-level and all 600-level or higher courses in the Applied Mathematics and Statistics Department (with the exception of seminar and research courses) are “graduate level” for the purpose of meeting the Master’s degree requirements. 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.

• Meet one of the following two 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.

• Demonstrate a working knowledge of the utilization of computers in applied mathematics and statistics.

In consultation with the faculty advisor, a candidate for the master’s degree plans a complete program of proposed course work and submits it in writing for departmental approval. This should be done early in the first semester of residence.

Doctoral students in other departments may undertake concurrently a master’s program in Applied Mathematics and Statistics. Application forms and information are 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:

<table>
<thead>
<tr>
<th>Core financial mathematics requirements (4 courses)</th>
<th></th>
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<tbody>
<tr>
<td>EN.550.442 Investment Science</td>
<td>4</td>
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<tr>
<td>or EN.550.642 Investment Science-Commodities as a Unique Asset Class</td>
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<tr>
<td>EN.550.444 Introduction to Financial Derivatives</td>
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<tr>
<td>EN.550.445 Interest Rate and Credit Derivatives</td>
<td>4</td>
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<tr>
<td>EN.550.448 Financial Engineering and Structured Products</td>
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<tr>
<td>or EN.550.446 Risk Measurement/Management in Financial Markets</td>
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<table>
<thead>
<tr>
<th>Core applied mathematics requirements (5 courses)</th>
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</thead>
<tbody>
<tr>
<td>EN.550.427 Stochastic Processes and Applications to Finance</td>
<td>4</td>
</tr>
<tr>
<td>EN.550.433 Monte Carlo Methods</td>
<td>3</td>
</tr>
<tr>
<td>EN.550.413 Applied Statistics and Data Analysis</td>
<td>4</td>
</tr>
<tr>
<td>EN.550.439 Time Series Analysis</td>
<td>4</td>
</tr>
<tr>
<td>EN.550.461 Optimization in Finance</td>
<td>4</td>
</tr>
</tbody>
</table>

**Electives**

3 elective courses:

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

**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.

### 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.
- Complete satisfactorily a one year elective course (or the equivalent) in some area of application of applied mathematics and statistics.
- Acquire teaching experience under the supervision of the faculty.
- 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.550.600 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.550.620), statistics (EN.550.630), and stochastic processes (EN.550.426);
- optimization (EN.550.661);
- numerical and matrix analysis (EN.550.681, EN.550.692); and
- discrete mathematics (EN.550.671, EN.550.672).

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

### Specialized Courses

Each student takes advanced courses appropriate to the proposed area of dissertation research, with the approval of the research advisor.

### Elective Courses

A one-year graduate course (or the equivalent) in a field distinct from the student's specialized area is required. This is a minimal requirement. Students are encouraged to take more than two semesters of 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. Although students are strongly encouraged to take the elective courses outside the department, with the approval of the advisor they may be chosen within the department, provided they are 600- or 700-level courses in a field clearly distinct from the student’s specialized area.
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 of Education
Edward R. Scheinerman
Professor: discrete mathematics, graph theory, social networks, random methods, partially ordered sets.

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

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

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
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.

Daniel Naiman
Professor and Director, Financial Mathematics Master’s Program: statistics, computational probability, bioinformatics.

Carey E. Priebe
Professor: statistics, image analysis, pattern recognition.

John C. Wierman
Professor: probability, statistics, discrete mathematics, percolation theory, stochastic processes.

Assistant Professors
Amitabha Basu
Assistant Professor: optimization, discrete and combinatorial geometry, convex analysis, operations research.

Maxim Bichuch
Assistant Professor: financial mathematics, utility optimization, market with transaction costs, counterparty risk, valuation adjustments

Tamas Budavari
Assistant Professor: computational statistics, Bayesian inference, low-dimensional embeddings, streaming algorithms, parallel processing on GPUs, scientific databases, survey astronomy

Nicolas Charon
Assistant Professor: shape analysis, image analysis, Riemannian and discrete geometry

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

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

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

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

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

Lecturers
Prashant Athavale
Lecturer: mathematical image processing, variational problems, multiscale analysis; bio-medical imaging

John Miller
**Joint, Part-Time and Visiting Appointments**

Gregory Chirikjian  
Professor: Mechanical Engineering, computational structural biology, applied mathematics, robotics.

John Goutsias  
Professor: Electrical and Computer Engineering.

Benjamin F. Hobbs  
Professor: Geography and Environmental Engineering, energy and environmental systems and economics.

Pablo Iglesias  
Professor: Electrical and Computer Engineering.

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

Scott Levin  
Assistant Professor: Emergency Medicine, School of Medicine.

David Marchette  
Lecturer: Naval Surface Warfare Center.

Michael I. Miller  
Professor: Biomedical Engineering.

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

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

**Courses**

**EN.550.100. Introduction to Applied Mathematics and Statistics.**  
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): E. Younes  
Area: Engineering, Quantitative and Mathematical Sciences.

**EN.550.103. Mathematics & Politics.**  
Instructor(s): M. Sedlock  
Area: Quantitative and Mathematical Sciences.

**EN.550.111. Statistical Analysis I.**  
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.550.420-EN.550.430.  
Prerequisites: Statistics Sequence restriction: students who have completed AS.230.205 or EN.550.113 may not enroll.;Statistics Sequence restriction: students who have completed any of these courses may not register: EN.550.211 OR EN.550.230 OR EN.550.310 OR EN.550.311 OR EN.550.420 OR EN.550.430 OR EN.550.413 OR EN.560.435 OR AS.280.345 OR AS.200.314 OR AS.200.315  
Instructor(s): Z. Lubberts  
Area: Engineering, Quantitative and Mathematical Sciences.

**EN.550.112. Statistical Analysis II.**  
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.550.420-430 sequence.  
Prerequisites: Prereqs: EN.550.111 OR EN.550.113 OR AS.230.205 OR AS.280.345 OR credit for AP Statistics  
Instructor(s): J. Paat  
Area: Engineering, Quantitative and Mathematical Sciences.

**EN.550.113. Statistics Through Case Study.**  
A case-study based course treating basic statistical theory and methodology. All theoretical material will be presented in the context of timely real-world case studies. Topics covered will include basic probability, random variables and their distributions, the central limit theorem and normal approximation, sampling distributions, statistical inference, confidence intervals, and hypothesis testing. Recommended Course Background: Four years of high school mathematics.  
Prerequisites: This course is not open to students who have received credit for 550.111 or AP Statistics.;Statistics Sequence restriction: AS.230.205 OR EN.550.211 OR EN.550.230 OR AS.280.345 OR AS.280.345 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.550.413  
Instructor(s): D. Athreya  
Area: Engineering, Quantitative and Mathematical Sciences.

**EN.550.171. Discrete Mathematics.**  
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; group theory; permutations and symmetry groups; graph theory. Selected applications. The concept of a proof and development of the ability to recognize and construct proofs are part of the course. Recommended Course Background: Four years of high school mathematics.  
Instructor(s): B. Castello  
Area: Quantitative and Mathematical Sciences.
EN.550.200. Computing for Engineers and Scientists.
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.500.200
Prerequisites: AS.110.107 OR AS.110.109 or credit for those courses through AP Calculus.
Area: Engineering, Quantitative and Mathematical Sciences.

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; 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
Instructor(s): P. Athavale
Area: Quantitative and Mathematical Sciences.

EN.550.230. Introduction to Biostatistics.
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
Instructor(s): K. Hernandez Cuevas
Area: Engineering, Quantitative and Mathematical Sciences.

As society’s enterprises and technologies grow more and more complex, their operation and planning rely increasingly on mathematics-based analyses. This course is an introduction to management science and the quantitative approach to decision making. Emphasis on model development and case studies, using spreadsheets or other computer software, applied to a variety of problems in manufacturing, transportation, finance, and general management.
Prerequisites: AS.110.106 or AS.110.108
Instructor(s): B. Castello
Area: Engineering, Quantitative and Mathematical Sciences.

This course is an introduction to management science and the quantitative approach to decision making. Our focus will be on the formulation and analysis of stochastic models, where some problem data may be uncertain. The covered topics may include Project Scheduling, Decision Analysis, Time Series Forecasting, Inventory Models with Stationary or Nonstationary Demand, Queuing Models, Discrete-Event Simulation, and Quality Management. We emphasize model development and case studies, using spreadsheets and other computer software. The applications we study occur in a variety of applications. Recommended Course Background: One semester of calculus
Prerequisites: AS.110.106 or AS.110.108
Instructor(s): B. Castello
Area: Engineering, Quantitative and Mathematical Sciences.

Prereq: Calculus I Overview of some of the more common computational platforms in which to do applied mathematics. The course will cover computing in at least three general areas: numerical linear algebra using Matlab, symbolic mathematics using Maple, and statistics using R. Students will be presented with applications, basic mathematics that underlies the problems to be solved, and computational approaches to their solution.
Instructor(s): D. Naiman
Area: Engineering, Quantitative and Mathematical Sciences.

EN.550.282. A Hands-On Introduction to MATLAB.
This is an introductory course in programming MATLAB for students in the mathematical sciences. MATLAB is widely used in research and industry for numerical calculations, plotting of functions and data, and the creation of user interfaces. Short tutorial lectures will be followed by problem solving sessions. Topics emphasized will be basic programming in the MATLAB environment and the practical solution of problems in matrix calculations, differential equations, signal and image processing, and machine learning.
Prerequisites: AS.110.201 OR AS.110.212 OR EN.550.291
Instructor(s): T. Ding
Area: Quantitative and Mathematical Sciences.

EN.550.283. Introduction to R.
This is an introductory course in R for both undergraduate and graduate students. R is a programming language and software environment that provides a wide variety of statistical and graphical techniques, including linear and nonlinear modeling, classical statistical tests, time-series analysis, etc. We will discuss data structures, data entry and manipulation, graphical procedures, statistical models, and programming in R. No previous programming experience is required.
Instructor(s): T. Bosede
Area: Quantitative and Mathematical Sciences.

EN.550.284. VBA For Finance.
Excel VBA is a powerful programming environment that lurks behind the Excel program that many of us have some familiarity with. This course aims to get students up to speed with working with this tool.
Instructor(s): D. Naiman

This is an introductory course in programming python for students in the mathematical sciences. Short tutorial lectures will be followed by problem solving sessions. Topics emphasized will include linear algebra problems, ordinary differential equations and optimization. Also a particular interest will be given to practical machine learning problems (classification, regression and clustering).
Instructor(s): K. Lahouel
Area: Quantitative and Mathematical Sciences.

EN.550.291. Linear Algebra and Differential Equations.
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.110.106 OR AS.110.108 ) AND ( AS.110.107 OR AS.110.109 )
Instructor(s): B. Castello
Area: Engineering, Quantitative and Mathematical Sciences.
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 course background: Co-requisite, Multivariable Calculus.
Prerequisites: ( AS.110.106 OR AS.110.108 ) AND ( AS.110.107 OR AS.110.109 ); Statistics Sequence restriction: students who have completed any of these courses may not register: EN.550.311 OR EN.560.435 OR EN.550.420 OR EN.550.430
Instructor(s): P. Athavale
Area: Engineering, Quantitative and Mathematical Sciences.

EN.550.311. Probability and Statistics for the Biological Sciences and Engineering.
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. This course will be at the same technical level as EN.550.310. Students are encouraged to consider EN.550.420-430 instead. Combinatorial probability, independence, conditional probability, random variables, expectation and moments, limit theory, estimation, confidence intervals, hypothesis testing, tests of means and variances, and goodness-of-fit will be covered. Students cannot receive credit for both EN.550.310 and EN.550.311. Students cannot receive credit for EN.550.311 after having received credit for EN.550.420 or EN.550.430. Recommended Course Corequisite: AS.110.202
Prerequisites: ( AS.110.106 OR AS.110.108 ) AND ( AS.110.107 OR AS.110.109 ); Statistics Sequence restriction: students who have completed any of these courses may not register: EN.550.310 OR EN.560.435 OR EN.550.420 OR EN.550.430
Instructor(s): P. Athavale
Area: Engineering, Quantitative and Mathematical Sciences.

EN.550.361. Introduction to Optimization.
Appropriate for undergraduate and graduate students without the mathematical background required for EN.550.661. 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 and graduate students without the mathematical background required for EN.550.661.
Prerequisites: EN.550.361 AND ( AS.110.202 OR AS.110.211 )
Instructor(s): D. Fishkind
Area: Engineering, Quantitative and Mathematical Sciences.

Computing experience. A first course in the mathematical theory of secure and reliable electronic communication. Cryptology is the study of secure communication: How can we ensure the privacy of messages? Coding theory studies how to make communication reliable: How can messages be sent over noisy lines? Topics include finite field arithmetic, error-detecting and error-correcting codes, data compressions, ciphers, one-time pads, the Enigma machine, one-way functions, discrete logarithm, primality testing, secret key exchange, public key cryptosystems, digital signatures, and key escrow. Recommended Course Background: AS.110.204
Prerequisites: EN.550.171 AND ( EN.550.291 OR AS.110.201)
Instructor(s): D. Fishkind
Area: Engineering, Quantitative and Mathematical Sciences.

In this course, we will study numerical methods, and scientific computing using the Python language. We will discuss topics in numerical analysis, such as equation solving, differential equations, interpolation, integration etc. We will also introduce image analysis techniques such as filtering, denoising, inpainting, and segmentation. We will discuss core computer language concepts, algorithms, and data-structures using Python. No previous experience with computer programming is needed.
Prerequisites: ( EN.550.291 OR AS.110.201 ) AND ( AS.110.202 OR AS.110.211 )
Instructor(s): P. Athavale
Area: Quantitative and Mathematical Sciences.

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.550.291 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.550.386. Scientific Computing: Differential Equations.**
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:** (EN.550.291 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.

A first course on computational differential equations in vector spaces and applications, a continuation of EN.550.385. 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.
Instructor(s): G. Eyink
Area: Engineering, Quantitative and Mathematical Sciences.

**EN.550.391. Dynamical Systems.**
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.550.291 OR AS.110.201 OR AS.110.211
Instructor(s): P. Athavale
Area: Engineering, Quantitative and Mathematical Sciences.

**EN.550.400. Mathematical Modeling and Consulting.**
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.550.361 OR EN.550.362
Instructor(s): B. Castello
Area: Engineering, Quantitative and Mathematical Sciences.

**EN.550.413. Applied Statistics and Data Analysis.**
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.550.112 or EN.550.310 or EN.550.311 or EN.550.420
Instructor(s): M. Tang
Area: Engineering, Quantitative and Mathematical Sciences.

**EN.550.415. Practical Scientific Analysis of Big Data.**
This course explores common issues around computational analysis of massive data. We will learn about numerical inaccuracies in calculations, work with databases, and venture out into parallel computing (multi-threading and CUDA). Students will be introduced to streaming algorithms and elements of robust statistics.
Instructor(s): T. Budavari
Area: Natural Sciences, Quantitative and Mathematical Sciences.

**EN.550.420. Introduction to Probability.**
Probability and its applications, at the calculus level. Emphasis on techniques of application rather than 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.550.620. Auditors are not permitted. Students can use any of the 6th, 7th or 8th editions of the textbook. Recommended Course Background: one year of calculus; Corequisite: multivariable calculus.
**Prerequisites:** Prereqs: 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 already completed EN.550.430 may not register
Instructor(s): F. Torcaso
Area: Engineering, Quantitative and Mathematical Sciences.

**EN.550.426. Introduction to Stochastic Processes.**
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 not earn credit for both EN.550.426 and EN.550.427.
**Prerequisites:** EN.550.420 AND (EN.550.291 OR AS.110.201 OR AS.110.212)
Instructor(s): F. Torcaso
Area: Engineering, Quantitative and Mathematical Sciences.
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. Students may not receive credit for both EN.550.427 and EN.550.426.
Prerequisites: Students may not receive credit for both EN.550.427 and EN.550.426.
Instructor(s): D. Naiman
Area: Engineering, Quantitative and Mathematical Sciences.

EN.550.428. Stochastic Processes and Applications to Finance II.
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.550.427
Instructor(s): J. Miller
Area: Quantitative and Mathematical Sciences.

EN.550.430. Introduction to Statistics.
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.550.420 OR APPROVED ALTERNATIVE AND (EN.550.291 OR AS.110.201 OR AS.110.212)
Instructor(s): D. Naiman
Area: Engineering, Quantitative and Mathematical Sciences.

Denoising, 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 E.M. 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): B. Jedynak
Area: Engineering, Quantitative and Mathematical Sciences.

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: EN.550.430
Instructor(s): J. Spall
Area: Engineering, Quantitative and Mathematical Sciences.

Nonparametric, or distribution-free methods for statistical data analysis design statistical decision regions under minimal assumptions on the observed data, avoiding, in particular, making the assumption that their distribution in known, or that it belongs to a specific parametric class (like 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 with an introduction to the problem of multiple comparisons.
Prerequisites: PREREQ: EN.550.310 OR EN.550.311 OR EN.550.430
Instructor(s): E. Younes
Area: Engineering, Quantitative and Mathematical Sciences.

EN.550.436. Data Mining.
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.550.413
Prerequisites: EN.550.310 or EN.550.311 or EN.550.430
Instructor(s): T. Budavari
Area: Engineering, Quantitative and Mathematical Sciences.

Managing and analyzing big data in finance can be of ultimate challenge but of ultimate opportunity. The need for statistical tools and machine learning techniques has been gradually influencing the marketplace. This course will explore several topics of machine learning and statistical finance, while the emphasis will be the applications on market prediction, risk detection and validity of finance models. The tentative topics include traditional finance models, linear models, kernel methods (e.g. support vector machine), hidden Markov models, decision trees, dimensionality reduction (e.g. PCA, low rank approximation), conditional modeling and conditional inference, and hypothesis testing. Students will be involved in several projects (computer experiments) to examine those tools with real market data. Recommended Course Background: EN.550.428
Prerequisites: (EN.550.420 OR EN.550.620) AND (EN.550.430 OR EN.550.630)
Instructor(s): L. Chang
Area: Engineering, Quantitative and Mathematical Sciences.

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.550.310 OR EN.550.311 OR EN.550.420) AND (AS.110.201 OR AS.110.212 OR EN.550.291)
Instructor(s): F. Torcaso
Area: Engineering, Quantitative and Mathematical Sciences.
EN.550.441. Equity Markets and Quantitative Trading.  
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.550.442 or instructor's permission

**Instructor(s):** J. Miller

**Area:** Engineering, Quantitative and Mathematical Sciences.

Intended for upper-level undergraduate and graduate students, 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. Some familiarity with optimization is desirable but not necessary.

**Instructor(s):** J. Miller

**Area:** Engineering, Quantitative and Mathematical Sciences.

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.550.427 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.550.444. Introduction to Financial Derivatives.  
This course will develop the mathematical concepts and techniques for modeling cash instruments and their hybrids and derivatives.

**Prerequisites:** AS.110.302 AND EN.550.420

**Instructor(s):** D. Audley

**Area:** Engineering, Quantitative and Mathematical Sciences.

EN.550.445. Interest Rate and Credit Derivatives.  
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.550.444. 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.550.444

**Instructor(s):** D. Audley

**Area:** Engineering, Quantitative and Mathematical Sciences.

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.

**Prerequisites:** EN.550.444

**Instructor(s):** D. Audley

**Area:** Engineering, Quantitative and Mathematical Sciences.

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:** Prereq: EN.550.442 OR EN.550.444

**Instructor(s):** D. Audley

**Area:** Engineering, Quantitative and Mathematical Sciences.

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).

**Instructor(s):** D. Audley

**Area:** Engineering, Quantitative and Mathematical Sciences.
EN.550.449. Advanced Equity Derivatives.
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, 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).
Prerequisites: EN.550.444
Instructor(s): J. Miller
Area: Engineering, Quantitative and Mathematical Sciences.

EN.550.450. Computational Molecular Medicine.
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.550.420 AND EN.550.430 ) OR equivalent courses in probability and statistics.
Instructor(s): D. Geman
Area: Engineering, Quantitative and Mathematical Sciences.

EN.550.453. Mathematical Game Theory.
The course will examine the mathematical tools and concepts used in analyzing sequential games, player games, games in rule-defined form. The roles of information and payoff, finite strategy sets, games with a continuum of strategies, N-player games, games in rule-defined form. The tools of information and memory. Selected applications to economic, recreational, and military situations. Prereq: Multivariable Calculus, probability, linear algebra.
Prerequisites: ( AS.110.202 OR AS.110.211 ) AND EN.550.420 AND ( EN.550.291 OR AS.110.201 )
Instructor(s): B. Castello
Area: Engineering, Quantitative and Mathematical Sciences.

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.

A survey of many of the more important optimization methods and tools that are found to be useful in financial applications.
Prerequisites: EN.550.442 OR EN.550.444
Instructor(s): R. Tappenden
Area: Engineering, Quantitative and Mathematical Sciences.

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: EN.550.361 or EN.550.661
Instructor(s): B. Castello
Area: Engineering, Quantitative and Mathematical Sciences.

EN.550.471. Combinatorial Analysis.
Recommended Course Background: AS.550.291 or AS.110.201
Instructor(s): E. Scheinerman
Area: Quantitative and Mathematical Sciences.

EN.550.472. Graph Theory.
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
Instructor(s): A. Basu
Area: Quantitative and Mathematical Sciences.

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): C. Lalescu
Area: Quantitative and Mathematical Sciences.
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.550.420 OR EN.550.310 OR EN.550.311 ) AND ( ( EN.550.291 ) OR ( AS.110.201 AND AS.110.302 ) )
Instructor(s): D. Athreya
Area: Natural Sciences, Quantitative and Mathematical Sciences.

EN.550.493. Mathematical Image Analysis.
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)
Instructor(s): N. Charon
Area: Engineering, Quantitative and Mathematical Sciences.

EN.550.500. Undergraduate Research.
Reading, research, or project work for undergraduate students. Pre-arranged individually between students and faculty.
Instructor(s): D. Fishkind; E. Scheinerman; Staff.

Instructor(s): J. Wierman.

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): F. Torcaso; Staff.

EN.550.503. Preparation for Research.
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 Permission Required - Opportunity for students to particiate
Instructor(s): B. Castello
Area: Quantitative and Mathematical Sciences.

Instructor(s): D. Fishkind
Area: Quantitative and Mathematical Sciences.

Preparation of a substantial thesis based upon independent student research, under the pre-arranged supervision of at least one faculty member in Applied Mathematics and Statistics. Instructor permission required.
Instructor(s): D. Geman; F. Torcaso.

EN.550.552. Undergraduate Internship.
Instructor(s): Staff.

EN.550.574. Research-Intersession.
Instructor(s): D. Fishkind; E. Scheinerman; J. Fill.

EN.550.590. Internship-Summer.
Instructor(s): Staff.

EN.550.597. Research-Summer.
Instructor(s): Staff.

EN.550.599. Independent Study.
Instructor(s): D. Fishkind; E. Scheinerman; J. Fill; N. Lee.

EN.550.600. Department Seminar.
A variety of topics discussed by speakers from within and outside the university. Required of all resident department graduate students.
Instructor(s): D. Robinson.

EN.550.620. Probability Theory I.
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.550.621 Probability Theory II, will cover classical limit theorems, characteristic functions, and conditional expectation.
Prerequisites: EN.550.420 and AS.110.405 or equivalent
Instructor(s): V. Lyzinski.

EN.550.621. Probability Theory II.
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 theory, Berry-Esseen theorem, infinitely divisible and stable laws.
Prerequisites: EN.550.620 OR AS.110.405
Instructor(s): J. Fill.

EN.550.622. Introduction to Stochastic Calculus.
A graduate-level class on stochastic calculus, providing a rigorous introduction on stochastic integrals and differential equations.
Prerequisites: EN.550.621
Instructor(s): M. Bichuch.
This course explores several topics and tools toward modern applications of probability and statistics in computational, cognitive, engineering, and neural sciences. The course will introduce the theoretical background for each topic, while the emphasis will be on the applications that are not often covered in the standard probability and statistics courses. The tentative topics include: Gibbs distribution and the maximum entropy with connections to large deviations and information theory; Nonparametric statistics ("learning theory") and classifications including consistency, bias/variance tradeoff, and regularization; Markov chains and their applications in MCMC computing and hidden Markov models; Graphical models and their applications; Parameter estimation, the EM algorithm and applications on image template learning. For each topic, there will be a related project assignment, which is composed of both paper work problems and computer experiments, designed to demonstrate the mathematics and the utility of the approach in the topic. Students are required to submit their own work individually.

Prerequisites: EN.550.310 OR EN.550.311 OR (EN.550.420 AND EN.550.430)
Instructor(s): L. Chang.

EN.550.630. Statistical Theory.
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: EN.550.420 or EN.550.620.
Instructor(s): C. Priebe.

EN.550.631. Statistical Theory II.
Advanced concepts and tools fundamental to research in mathematical statistics and statistical inference: asymptotic theory; optimality; various mathematical foundations.
Instructor(s): C. Priebe.

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: 550.630 (recommended) or 550.430

Prerequisites: EN.550.630 OR EN.550.430
Instructor(s): Y. Xu.

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.550.632 or permission from the instructor
Instructor(s): Y. Xu.

EN.550.635. Topics in Bioinformatics.
A "readings" course organized around research articles in the recent bioinformatics and computational biology literatures. In this term, the choice of papers will favor work on inferring phenotype from genotype, and modeling signaling networks, based on gene microarrays bearing the expression levels of thousands of transcripts, and on properties of proteins, such as predicting active sites and detecting harmful mutations. One major objective is to prepare students to comfortably read articles which involve extensive mathematical and statistical modeling as well as techniques from pattern recognition and machine learning. Most papers will be presented by the students. In addition, student expositions will be preceded by "tutorials" by the instructor on various aspects of statistical learning, modeling and prediction, such as properly estimating generalization error in cancer classification and avoiding over-fitting in learning networks of molecular interactions. Recommended Course Background: course in statistics; previous exposure to machine learning or pattern recognition
Instructor(s): D. Geman.

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., 550.430 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.550.642. Investment Science-Commodities as a Unique Asset Class.
The aims of the course are the following: 1. understand the properties of commodities and shipping as an asset class distinct from bonds and equity, 2. learn the fundamental economic results, e.g., theory of storage, established for commodities by leading figures like Keynes and Kaldor, 3. recognize the specific difficulties of the different groups, i.e., energy, metals, agricultural and shipping, 4. analyze the forward curve and its stochastic modeling, with or without seasonality, 5. discuss the pricing and hedging of options mostly traded in commodity markets, such as Asian and spread, as well as the valuation of physical assets through alternative approaches, 6. identify the different ways of investing in Commodities: Futures, ETFs, indexes, structured notes. Students should have rudimentary knowledge of financial markets.  
Prerequisites: Rudimentary knowledge of financial markets; EN.550.420 and (AS.110.106 or AS.110.108)
Instructor(s): H. Geman.

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): L. Chang.

EN.550.646. Advanced Topics in Derivatives.
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.

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.

Credit risk is a topic which has become of fundamental importance after the recent crisis, due to the larger number of credit quality deteriorations and default events. This course deals with mathematical modeling and valuation of credit risk. Students will be exposed to key theoretical principles (doubly stochastic intensity processes, enlargement of filtrations, risk measures), related to the construction of modern credit risk management systems. The course will analyze computational techniques for simulating default times, as well as methodologies for measuring credit losses based on probabilistic tools. We will discuss topics of currently high research interest, such as counterparty risk valuation, systemic risk, liquidity risk, and default contagion.  
Prerequisites: (EN.550.426 OR EN.550.427) AND EN.550.620  
Instructor(s): A. Capponi.

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 and project undertaking. 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). 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 fundamentals of interest rates and stochastic modelling of the yield curve to price caps, floors and swaptions. It will conclude with the Asset Liability Management of a bank, insurance company. This course will not begin until mid-October.  
Instructor(s): H. Geman.

EN.550.650. Statistical Models in Molecular Medicine.
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. The course will cover core statistical methodologies, including machine learning, stochastic processes and statistical inference. Recommended Course Background: EN.550.420 and EN.550.310/EN.550.311/EN.550.430.

Advanced introduction to no-arbitrage derivatives pricing theory. Topics include fundamental theorems of asset pricing; equivalent martingale measures; stochastic volatility models; credit-linked derivatives; stochastic control & optimal stopping problems in finance. This course assumes a working familiarity with Brownian motion and Ito's formula. Simulation and numerical methods for derivatives pricing will also be discussed.  
Prerequisites: EN.550.426 OR EN.550.427 OR EN.550.440 OR EN.550.621.
EN.550.653. Commodities and Commodity Markets.
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.550.420 and AS.110.106 or AS.110.108
Instructor(s): G. Schultz; H. Geman.

This course considers algorithms for solving various important nonlinear optimization problems and, in parallel, develops the supporting theory. Primary focus will be on unconstrained and bound-constrained optimization. Topics will include: necessary and sufficient optimality conditions; gradient, Newton, and quasi-Newton based line-search and trust-region methods; linear and nonlinear least-squares problems; linear and nonlinear conjugate gradient methods; stochastic optimization; optimal gradient methods; structured nonsmooth optimization, and derivative-free optimization. Special attention will be paid to the large-scale case and will include topics such as limited-memory quasi-Newton methods, projected gradient methods, and subspace accelerated two-phase methods for bound-constrained optimization. Recommended Course Background: Multivariable Calculus, Linear Algebra; Coreq: AS.110.405
Instructor(s): D. Robinson.

This course considers algorithms for solving various nonlinear constrained optimization problems and, in parallel, develops the supporting theory. Topics include: necessary and sufficient optimality conditions for constrained optimization; projected-gradient and two-phase accelerated subspace methods for bound-constrained optimization; simplex, interior-point, Bender’s decomposition, and the Dantzig-Wolfe decomposition methods for linear programming; duality theory; 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.
Instructor(s): S. Arguillere.

EN.550.663. Stochastic Search & Optimization.
An introduction to stochastic search and optimization, including discrete and continuous optimization problems. Topics will include the “no free lunch” theorems, beneficial effects of injected Monte Carlo randomness, algorithms for global and local optimization problems, random search, recursive least squares, stochastic approximation, simulated annealing, evolutionary and genetic algorithms, machine (reinforcement) learning, and statistical multiple comparisons. Students should have knowledge of basic matrix algebra. Recommended Course Background: Graduate course in probability and statistics
Instructor(s): J. Spall.

Concepts and statistical techniques critical to constructing and analyzing effective simulations; emphasis on generic principles rather than specific applications. Topics include model building (bias-variance tradeoff, model selection, Fisher information), benefits and drawbacks of simulation modeling, random number generation, simulation-based optimization, discrete multiple comparisons using simulations, Markov chain Monte Carlo (MCMC), and input selection using optimal experimental design.
Instructor(s): J. Spall.

This course presents algorithms for convex optimization along with the supporting theoretical convergence results. The chosen topics covered, which are driven by big data and machine learning applications, include convex sets and functions, gradient methods (steepest descent, line searches, rates-of-convergence for weakly and strongly convex functions, Frank-Wolfe method), accelerated methods (heavy ball, Nesterov), stochastic gradient, coordinate descent, proximal and projected gradient methods, duality theory and duality-based algorithms (augmented Lagrangian, ADMM), and Newton/quasi-newton methods. Recommended Course Background: (AS.110.201 or AS.110.212 or EN.550.291) and AS.110.405.
Instructor(s): D. Robinson.

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.550.671. Combinatorial Analysis.
An introduction to combinatorial analysis at the graduate level. Meets concurrently with 550.471. See 550.471 for course description. Recommended Course Background: EN.550.291 or AS.110.201
Instructor(s): E. Scheinerman.

EN.550.672. Graph Theory.
An introduction to graph theory at the graduate level. See 550.472 for course description. Meets with EN.550.472
Prerequisites: EN.550.291 OR AS.110.201 OR AS.110.212
Instructor(s): A. Basu.

The purpose of this class is to provide an elementary knowledge of the differential geometry of curves and surfaces, and to place this in relation with the description and characterization of 2D and 3D shapes. Intrinsic local and semi-local descriptors, like the curvature or the second fundamental form will be introduced, with an emphasis on the invariance of these features with respect to rotations, translations, etc. Extension of this point of view to other class of linear transformations will be given, as well as other types of shape descriptors, like moments or medial axes. Recommended Course Background: Calculus III and linear algebra
Instructor(s): E. Younes
Area: Engineering, Quantitative and Mathematical Sciences.

Brief review of topics in elementary numerical analysis such as floating-point arithmetic, Gaussian elimination for linear equations, interpolation and approximation. Core topics to be covered: numerical linear algebra including eigenvalue and linear least-squares problems, iterative algorithms for nonlinear equations and least squares problems, and convergence theory of numerical methods. Other possible topics: sparse matrix computations, numerical solution of partial differential equations, finite element methods, and parallel algorithms.
Instructor(s): N. Charon.

This class will explore basic aspects of functional analysis, focusing mostly on normed vector spaces. This will include, in particular, the Hahn-Banach and open mapping theorems, a discussion of strong and weak topologies, the theory of compact operators, and spaces of integrable functions and Sobolev spaces, with applications to the study of some partial differential equations. Recommended Course Background: AS.110.415/AS.110.416/AS.110.605 or EN.550.620
Prerequisites: AS.110.405 or equivalent
Instructor(s): E. Younes.

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.550.361 or higher) and (AS.110.202 OR AS.110.211 or higher) AND AS.110.302 or higher.
Prerequisites: ( AS.110.202 OR AS.110.211 or higher) AND ( AS.110.302 or higher)
Instructor(s): E. Younes.

EN.550.690. Neural Networks and Feedback Control Systems.
This roundtable course is an introduction to two related areas#neural networks 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.

This course is open only to AMS department master's students.
Instructor(s): D. Audley; D. Naiman.

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: ( AS.110.202 OR AS.110.211 ) AND ( AS.110.201 OR AS.110.212 OR EN.550.291 ) AND AS.110.405
Instructor(s): D. Fishkind.

EN.550.693. Turbulence Theory.
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. Students should have previous familiarity with fluid mechanics.
Instructor(s): G. Eyink.

EN.550.694. Turbulence Theory II.
This course will continue the theoretical investigation of fluid turbulence, directly following on from EN.550.693. Topics to be considered are turbulent vortex dynamics, Lagrangian dynamics, and special topics such as wall-bounded turbulence, free shear flows, two-dimensional and quasigeostrophic turbulence, MHD turbulence, etc. Cross-listed with Physics
Prerequisites: EN.550.693
Instructor(s): G. Eyink.
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.

his course will discuss turbulence theory relevant for planetary atmospheres and oceans (including Earth's) and astrophysical plasmas. The three basic topics will be two-dimensional & geostrophic turbulence, compressible fluid turbulence, and magnetohydrodynamic turbulence. It would be useful for students to have taken courses EN.550.693-694, but these are not formal prerequisites and material from those courses will be reviewed as required. Exact mathematical results will be developed wherever possible to inform physical theories. The course focuses on coarse-grained nonlinear dynamics, turbulent cascades, wave-turbulence interactions, scaling theories, and relevant experimental observations from satellites and spacecraft.
Instructor(s): G. Eyink.

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. Pre-requisites: Multivariate Calculus, Linear Algebra, Differential Equations. Some familiarity with Optimization is recommended, but not mandatory.
Instructor(s): S. Arguillere.

EN.550.700. Master's Research.
Reading, research, or project work for Master's level students. Arranged individually between students and faculty.
Instructor(s): Staff.

EN.550.701. Graduate Independent Study.
Instructor(s): C. Priebe; E. Vishniac.

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.
Instructor(s): J. Fill.

EN.550.730. Topics In Statistics.
Roundtable course covers system identification and maximum likelihood for models, including EM (expectation-maximization) and variants, online versus offline estimation, role of feedback in estimation (open-loop versus closed-loop), and uncertainty bounds. Students should have an understanding of matrix theory and ordinary differential equations. Prior experience in data analysis and algorithms will be helpful. Recommended Course Background: EN.550.430; in particular, students should have prior exposure to maximum likelihood and Bayes’ rule.
Instructor(s): M. Tang.

EN.550.735. Topics in Statistical Pattern Recognition.
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. Recommended Course Background: EN.550.735
Instructor(s): M. Tang.

This course will cover various topics in financial mathematics and will be co-taught in two parts Part one (Chavez-Bedoya) will cover various aspects of portfolio optimization, and part two (Geman) will cover topics including stochastic time changes, subordination, pure jump Lévy Processes; the Lévy- Kintchine and its relationship to the Fast Fourier transform of option prices. The last part will be dedicated to general changes of probability measure in finance.
Instructor(s): H. Geman; L. Chavez-Bedoya.

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.

One of the most powerful tools currently applied in combinatorics. This course covers the basic method, with applications to graph theory, combinatorics, and especially algorithm design.
Instructor(s): V. Lyzinski.
EN.550.790. **Topics In Applied Math.**
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, Poissonization (and de-Poissonization), 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.550.800. **Dissertation Research.**
Instructor(s): Staff.

EN.550.803. **Financial Computing Workshop.**
Open to students in the Financial Mathematics Master’s Program only.
Instructor(s): Y. Li.

EN.550.805. **Communications Practicum.**
Open to students in the Financial Mathematics Master’s Program only.
Instructor(s): J. Heiserman.

EN.550.810. **Probability & Statistics.**
Instructor(s): C. Priebe.

EN.550.865. **Optimization and Discrete Math.**
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.550.892. **Matrix Analysis II Seminar.**
Continuation of EN.550.692.
Instructor(s): D. Fishkind.

**Cross Listed Courses**

**Biomedical Engineering**

EN.580.694. **Statistical Connectomics.**
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 (e.g., R, Python, Matlab).
Instructor(s): J. Vogelstein
Area: Engineering.

**Computer Science**

EN.600.442. **Modern Cryptography.**
This course focuses on cryptographic algorithms, formal definitions, hardness assumptions, and proofs of security. Topics include number-theoretic problems, pseudo-randomness, block and stream ciphers, public-key cryptography, message authentication codes, and digital signatures. Recommended Course Background: EN.600.226 and a 300-level or above systems course; EN.600.271/EN.600.471 and EN.550.171 or equivalent.
Instructor(s): A. Jain
Area: Engineering, Quantitative and Mathematical Sciences.

EN.600.675. **Statistical Machine Learning.**
This is a second graduate level course in machine learning. It will provide a formal and in-depth coverage of topics at the interface of statistical theory and computational sciences. We will revisit popular machine learning algorithms and understand their performance in terms of the size of the data (sample complexity), memory needed (space complexity), as well as the overall computational runtime (computation or iteration complexity). We will cover topics including nonparametric methods, kernel methods, online learning and reinforcement learning, as well as introduce students to current topics in large-scale machine-learning and randomized projections. Topics will vary from year-to-year but the general focus would be on combining methodology with theoretical and computational foundations. [Analysis or Applications]
Prerequisites: EN.600.475 OR EN.600.476 OR EN.600.676 OR permission of the instructor.
Instructor(s): R. Arora.