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rosion and Environmental Fracture of
terials

details the phenomena of environmental ı of metallic materials, and related engi- tions. Corrosion and fracture mechanisms zed and illustrated through actual failures es. Engineering solutions to be covered ınic and inorganic coating schemes, passi- nic protection, alloy design and selection, orrosion design criteria. Accelerated envi- sting techniques and their relation to actual expectancy are considered. Prerequisites: chemistry, 510.403 or 510.612, or permis- ıctor. (1.0 design credit)
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lification: Theory and Processes

overs the fundamentals of nucleation and ey pertain to solidification and examine a olidification processes such as welding, cation, and conventional casting. Prereq- 4 or permission of instructor.
3 hours

duction to Composites

overs the fundamental aspects of both con- liscontinuously fiber reinforced compos- Emphasis is placed on continuous fiber x composites. Material characteristics, fab- cts and micromechanical and macrome- erial characteristics are discussed. Topics evelopment and utilization of laminated or determination of material properties of composite laminates, flat plate design s, fabrication methods and applications. 510.611 or permission of instructor.
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laterials Science and Engineering

an individually tailored, supervised pro- s the student some research experience on a special problem related to his or her t. On completion of this course, a written submitted. Final approval of the essay will faculty adviser. Recommended: all other hould have been taken prior to this pro- cted concurrently with it. Limited to stu- I.M.S.E. program.
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Mathematical Sciences

The Department of Mathematical Sciences 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 five branches of modern applied mathematics: *Probability*, the science of mathematical representation and modeling of uncertainty; *Statistics*, the science of making decisions using data; *Operations Research*, the science of design, analysis and empirical study of actual operations and processes; *Optimization*, the science of determining best or optimal decisions; and *Discrete Mathematics*, the science of finite structures, arrangements, and relations. The curriculum also includes computing, matrix theory, numerical analysis, and other important topics in applied mathematics.

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, extraction of important implications of probability models, 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 theory, computer modeling, stochastic modeling, and game theory to problems such as allocation of resources, network flow, optimal facility location, planning and policy, scheduling, and ecosystems analysis. *Discrete Mathematics* includes the traditional themes of graph theory and combinatorics, as well as newer topics arising from modern technological and theoretical developments. In each of these general areas, the curriculum is structured through the Ph.D. level. The fourth general area, *Computational and Applied Mathematics*, covers topics vital or supportive in practice or in advanced study: computing, numerical analysis, advanced matrix analysis, and mathematical modeling. In all, the various mathematical science disciplines represented in the department are coherent and fitting partners comprising a relevant spectrum of modern applied mathematics.

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

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

The undergraduate major in mathematical sciences 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.

The Faculty

Lenore J. Cowen, Assistant Professor: combinatorics, discrete mathematics, graph algorithms.

James A. Fill, Professor: probability, stochastic processes, statistics.

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Alan J. Goldman, Professor: operations research, game theory, optimization, graph theory.

Leslie A. Hall, Assistant Professor: combinatorial optimization.

Shih-Ping Han, Professor: nonlinear optimization, optimization algorithms, numerical analysis.

Lancelot F. James, Assistant Professor: statistical inference, survival analysis.

Daniel Q. Naiman, Professor: statistics, probability.

Jong-Shi Pang, Professor: mathematical programming, network equilibrium, parallel optimization, linear complementarity.

Carey S. Priebe, Assistant Professor: statistics, image analysis, functional estimation.

Edward R. Scheinerman, Professor: combinatorics, graph theory.

John C. Wierman, Professor (Chair): probability, statistics, random graphs.

Colin Wu, Assistant Professor: statistics, semi-parametric models, robustness.

Facilities

The department is located in Maryland Hall. Office space and liberal access to microcomputers and X-terminals are provided to resident graduate students. A Reading/Commons Room provides opportunity for informal discussions among faculty and graduate students. The University's Milton S. Eisenhower Library maintains an excellent collection of literature in the mathematical sciences, including all of the important current journals.

Undergraduate Programs

The undergraduate major in mathematical sciences may serve as preparation for employment as a mathematical scientist, as preparation for graduate study in the mathematical sciences or related areas, or as a general quantitative education preparatory to a career in business, medicine, or other fields. An undergraduate major in mathematical sciences 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, for example in the Department of Computer Science (operating systems, digital systems, computational models, analysis of algorithms, data base systems). By suitable choice of electives, heavy concentration in a specific field of engineering is possible.

In order to develop a sound program suited to individual needs and interests, the student should consult regularly with the faculty adviser. Sample programs for various options and areas of concentration, and supplemental information, may be obtained from the department office.

With the advice and consent of the faculty adviser, each student constructs an individualized program meeting the requirements below. A written copy of the program should be on file with the faculty adviser, 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 requirements of the School of Arts and Sciences or of the School of Engineering, respectively, the general University distribution requirements, and the departmental requirements. *See General Requirements for Departmental Majors, page 45, and Writing Requirement, page 42.*

All courses used to meet the following departmental requirements must be passed with grade of C- or higher:

12 1. Three semesters of calculus: 110.108, 110.109, and ~~110.202~~ satisfy this requirement. Advanced placement is acceptable as well.

4 2. A course in linear algebra: 550.291, 550.191, or 110.201 is acceptable.

4 1 3. A course in computing: 550.186, 500.100, 600.108, or 600.109 is acceptable. (Other courses may be substituted with adviser's approval.)

4 4. A course in discrete mathematics: 550.171, 550.371, 550.371, 550.471 or 550.472 is acceptable. (This requirement applies to students entering the university in fall 1995 or after.)

5. At least five approved Mathematical Sciences courses numbered 300 or higher, including an optimization course (550.361) and two courses in probability and statistics from

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Departmental Majors, page
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6. Additional courses coded (Q) to reach a total of 40 credits coded (Q), of which at least 18 credits must be in courses numbered 300 or higher.

7. At least three semesters of approved coursework in some area of application of the mathematical sciences. These courses are to constitute a coherent program, and at least one course must be numbered 300 or higher. Appropriate fields include, but are not restricted to, biology, biomedical engineering, biophysics, chemical engineering, chemistry, civil engineering, computer science, earth and planetary sciences, economics, electrical engineering, geography and environmental engineering, mechanical engineering, physics, psychology, sociology, and systems analysis for public decision making.

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Requirements 1-5 together constitute a minimal core program, allowing maximum flexibility in planning degree programs. Students often are able to complete a second major during a four-year program or to proceed to the department's combined bachelor's/master's degree program.

It is highly recommended that additional departmental courses be taken in order to establish a broad foundation for a career as an applied mathematician. Of particular importance are additional courses in optimization (550.362), stochastic processes (550.426), statistics (550.413, 550.432, 550.433, 550.434), numerical methods (550.382), dynamical systems (550.391), and mathematical modeling (550.400). Students planning to continue to graduate school in a mathematical sciences program are encouraged to consider taking one or more graduate level courses in probability (550.620, 550.621), statistics (550.630, 550.631), optimization (550.661, 550.662), combinatorics (550.671), graph theory (550.672), numerical analysis (550.681), or matrix analysis (550.692). Students anticipating graduate work in the mathematical sciences should be aware that at least a reading knowledge of French, German, or Russian is widely required for a graduate degree.

For information on the combined bachelor's/master's program, see the description of Graduate Programs below.

Graduate Programs

A wide variety of advanced courses, seminars, and research opportunities is available in the Department of Mathematical Sciences. In addition to graduate programs in probability, statistics, operations research, optimization, and discrete mathematics, advanced study is possible in numerical analysis and matrix analysis, as well as 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 Mathematical Sciences 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 are asked to complete a brief pre-application form for initial evaluation. Those who are invited to apply 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 letter describing anticipated professional goals, and Graduate Record Examination (GRE) scores. The GRE testing program will change significantly in 1997, and this change will affect the graduate admissions requirements. Our current requirement is that all applicants submit

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scores from the GRE General Test. The department prefers to receive the score of the GRE subject test in mathematics, but may also accept the score of the subject test in the candidate's undergraduate major. However, once the new GRE is introduced, applicants should take the package of General Test measures containing the Mathematical Reasoning Test. Foreign students must submit scores from the Test of English as a Foreign Language (TOEFL).

Most applicants will have undergraduate majors in quantitative fields such as mathematics, statistics, engineering, or science, 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

Students may work toward either the Master of Arts (M.A.) degree or the Master of Science in Engineering (M.S.E.) degree. Both degrees ordinarily require a minimum of two consecutive 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 adviser. All 600- and 700-level courses are satisfactory for this requirement. Several 400-level courses are also acceptable. All courses must be completed with grades of B- or higher.
- Meet one of the following three options: (a) pass one of the five parts of the written qualifying examination (discussed under the Requirements for the Ph.D. Degree); (b) submit an acceptable research report based on an approved project; or (c) complete satisfactorily two additional one-semester graduate courses, as approved by the faculty adviser.
- Demonstrate a working knowledge of the utilization of computers in the mathematical sciences.

In consultation with the faculty adviser, 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 mathematical sciences. Application forms and information are available in the department office.

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 mathematical sciences. Interested students should apply not later than fall semester of their junior year.

The requirements for this program consist of those for the bachelor's and master's programs, as well as:

- At least two consecutive semesters of full-time residence after admission to the program.
- Satisfactory completion of at least 145 course credits.

As part of the application for admission to this program, a student submits a current transcript and a complete proposed program of course work which will meet the requirements. Application forms are available in the department office.

Requirements for the Ph.D. Degree

The objective of the department's Ph.D. program is to produce graduates who are broadly educated in the mathematical sciences 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 background, and affords a close view of the doctoral research process and of potential research areas and advisers. Continuation to advanced study and dissertation research is based upon favorable evaluation of preparedness and potential. A formal evaluation is normally made during the January Intersession in the student's second year of graduate study. A further evaluation is made in the third year. The culmination of the program is the doctoral dissertation, representing an original y in the first semester of

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and significant contribution to knowledge in the mathematical sciences.

Course requirements describe the nature of certain skills or knowledge which should be acquired. This may be accomplished by participation in formal courses or by other means.

Basic Courses

All students are expected to master introductory material in probability (550.420 or 550.620); statistics (550.430 or 550.630) or stochastic processes (550.426); optimization (550.661); operations research (550.453 or 550.463); matrix analysis (550.692); discrete mathematics (550.671, 550.672), and computational and applied mathematics (550.681, 550.695). 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. Sample programs in areas such as probability, statistics, discrete mathematics, operations research, optimization, and numerical analysis are available in the department office, but a student with different goals may pursue an appropriate program meeting the approval of the research adviser.

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 courses in other departments are econometrics, mathematical economics, mathematical ecology, computer engineering, systems theory, health systems, mathematics, urban studies, 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 adviser 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.

Qualifying Examination and Student Evaluation

The Ph.D. qualifying examination seeks to assess the student's knowledge and mastery of basic mathematical science disciplines, potential for innovative and creative work, and facility with applications of methodology. It is normally taken toward the end of the January intersession in the second year of residence. The student has, therefore, three semesters in which to acquire knowledge and develop maturity, with the early part of the intersession serving as a convenient period for final preparation. The results of the examination are considered along with performance in course work and other relevant information, in order to develop a thorough and helpful assessment of the student's progress and potential.

The examination is offered in five written parts, covering the five topic areas discussed above:

I. Probability
II. Statistics
III. Operations Research and Optimization
IV. Numerical and Matrix Analysis
V. Discrete Mathematics

The student must pass three of the written parts and complete at least one course in at least one of the other two areas.

Oral Examinations

The Graduate Board oral examination covers specialized and elective course work and prospective dissertation research. It is normally taken in the third year of residence, shortly after a departmental oral examination is taken as preparation.

Doctoral Dissertation

This represents the highlight and culmination of the Ph.D. program. It is a manuscript giving proper exposition of the findings of a program of original research. The dissertation must be approved by at least two faculty readers and certified by them as containing significant contributions to knowledge worthy of publication

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in scholarly journals. The candidate defends the dissertation in an open examination conducted by the department.

Other Requirements

Further elements of the Ph.D. program are

- Acquisition of teaching experience under faculty supervision.
- Demonstration of a working knowledge of the use of computers in the mathematical sciences.

Additional information about the graduate program is available from the department office.

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. The department also awards the Rufus P. Isaacs Fellowship, named in honor of a late member of the faculty acclaimed for his contributions to operations research. Isaacs Fellows receive supplemental financial aid and reduced assistantship duties. In addition, summer employment opportunities are often available within the University and in the Baltimore-Washington area.

Undergraduate Courses

Prospective students are invited to discuss with individual instructors the aims and prerequisites of their courses; formal prerequisites are listed to indicate the level and type of background expected and may be waived by the instructor for a student with suitable alternative preparation.

550.100 (Q,E) Orientation Seminar in Mathematical Sciences
A seminar-style series of lectures and assignments to acquaint the student with a range of intellectual and professional activities performed by mathematical scientists. Problems arising in the mathematical sciences and their applications will be presented by department faculty and outside speakers. Prerequisite: 110.108.
Wierman 1 credit spring

550.111 (Q,E) Statistical Analysis I
First semester of a general survey of statistical methodology. Topics include descriptive statistics, probability models, random variables, expectation, sampling, the central limit theorem, classical and robust estimation of location, confidence intervals, hypothesis testing, two-sample problems, introductory analysis of variance, introductory nonparametric methods. Three lectures and a conference weekly. Some use of computer terminals and the S+ statistical package, but prior computing experience not required. Prerequisites: four years of high school mathematics. Not open to mathematical sciences majors, who should take 550.310 or 550.420-430 instead. Students who may wish to undertake more than two semesters of probability and statistics should consider 550.420-430 or 550.620-630.
Fill, Wu 4 credits fall

550.112 (Q,E) Statistical Analysis II
Second semester of a general survey of statistical methodology. Topics include least squares and regression analysis, correlation, further nonparametric methods, chi-square tests, the likelihood concept, decision theory, Bayesian inference, time series, simultaneous equations, sample survey design. Prerequisite: 550.111. Not open to mathematical sciences majors, who should take 550.310 instead. Students who may wish to undertake more than two semesters of probability and statistics should consider 550.420-430 or 550.620-630.
Fill, Wu 4 credits spring

550.131 (Q,E) Quality Improvement
Introduction to techniques for continuous improvement of the quality of output of a process. Emphasis on total quality management, statistical process control (control charts), and diagnostic techniques. Intended for engineering undergraduates. *Formerly 550.121.*
Wierman 1.5 credits fall

550.171 (Q,E) 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 will be part of the course. Prerequisite: four years of high school mathematics.
Cowen, Scheinerman 4 credits fall

550.186 (Q,E) Introductio[n] Applications
Introduction to computing resources and available sof[tware] ing in engineering, scienc[e] sciences. Topics are chos[en] VMS(VAX) and UNIX syst[ems] cessing using LaTeX and analysis, FORTRAN, sta[tistical] MINITAB or SAS, IMSL nu[merical com]putations and graphics wi[th] ment, symbolic comput[ation] Maple, communications ous experience with com[puters] requisite: one semester o[f] *1995.*
Han 4 credits spr[ing]

550.191 (Q,E) Linear Alg[ebra]
Intended for majors in e[ngineering] matical and physical sc[iences] mental concepts and te[chniques] and matrix theory that a[re] systems of linear equatio[ns] formations, bases, matr[ices] values and eigenvecto[rs] approximations and le[ast] bers, quadratic forms, factorizations. The MA[TLAB] tem is used to motivate ition as well as to han[dle] exercises. Prerequisites some experience with c[omputers] Homewood Computin[g] Not open to students 110.201. *Last offered spr[ing]*
4 credits

550.291 (Q,E) Linear [...] Equations
An introduction to th[e] bra, matrix theory, a[nd] are used widely in mo[...] Intended for enginee[ring] program does not pe[rmit] 110.302. Prerequisites and some experience ing Facility's VAX/V[...]
Goldman, Pang, Sche[...]

550.310 (Q,E) Proba[bility]
An introduction to calculus level, intend[ed] students planning to ics. Students are enc[ouraged]

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ear stipend are available to
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ould consider 550.420-430 or

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Improvement

ques for continuous improve-
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Mathematics

athematics of finite systems.
induction and recursion; sets,
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lidean algorithm; group the-
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ons. The concept of a proof
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4 credits fall

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550.186 (Q,E) Introduction to Computing Applications

Introduction to computing, using campus computer resources and available software, for students majoring in engineering, science, and the mathematical sciences. Topics are chosen from introduction to VMS(VAX) and UNIX systems, text editors, text processing using LaTeX and Wordperfect, spreadsheet analysis, FORTRAN, statistical computing using MINITAB or SAS, IMSL numerical subroutines, computations and graphics with MATLAB, data management, symbolic computing using MACSYMA or Maple, communications and electronic mail. Previous experience with computing not required. Prerequisite: one semester of calculus. *Last offered spring 1995.*

Han 4 credits spring

550.191 (Q,E) Linear Algebra for Applications

Intended for majors in engineering and the mathematical and physical sciences. Emphasizes fundamental concepts and techniques of linear algebra and matrix theory that are used in many disciplines: systems of linear equations, vector spaces, linear transformations, bases, matrices, similarity, rank, eigenvalues and eigenvectors, orthogonality, norms, approximations and least squares, condition numbers, quadratic forms, canonical forms, and matrix factorizations. The MATLAB computer software system is used to motivate the student's conceptual intuition as well as to handle realistic computational exercises. Prerequisites: 110.108-109 or equivalent; some experience with computing, preferably with the Homewood Computing Facility's VAX/VMS system. Not open to students who have taken 110.211 or 110.201. *Last offered spring 1992.*

4 credits

550.291 (Q,E) 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 550.191 and 110.302. Prerequisites: 110.108-109 or the equivalent, and some experience with the Homewood Computing Facility's VAX/VMS system.

Goldman, Pang, Scheinerman 4 credits fall/spring

550.310 (Q,E) Probability and Statistics

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. Students are encouraged to consider 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, intervals, hypothesis testing, test of means and variances, goodness-of-fit. Prerequisite: one year of calculus. Recommended corequisite: 110.202.

4 credits

550.361-362 (Q,E) Introduction to Optimization

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. Prerequisites for 550.361: 110.108-109, 550.186, and 550.191 or approved alternative. Prerequisites for 550.362: 550.361, 110.202. Appropriate for undergraduate and graduate students without the mathematical background required for 550.661.

Goldman, Hall 4 credits every year

550.371 (Q,E) Cryptology and Coding

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. Prerequisites: 550.171 (110.204 may be acceptable with permission of instructor); 550.291 or 110.201.

Scheinerman 4 credits spring

550.382 (Q,E) Introduction to Numerical Methods

General tools and techniques for the numerical solution of mathematical problems and analysis of solution algorithms, treated at the level of first-year calculus and elementary linear algebra. Topics include floating-point arithmetic, interpolation and approximation, Gaussian elimination for linear equations, numerical differentiation and integration, numerical solution of difference and ordinary differential equations, and boundary value problems. Corequisites: 110.202 and 550.291 or approved alternative.

Han 4 credits spring

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550.391 (Q,E) 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, Liapunov 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: 110.202 and 550.291 or approved alternative.
Goldman, Scheinerman 3 credits fall

550.400 (Q,E) Mathematical Modeling Seminar
Formulation, analysis, interpretation, and evaluation of mathematical models. Synthesis of ideas, techniques, and models from mathematical sciences, science, and engineering. Case studies to illustrate basic features of the modeling process. Project-oriented practice and guidance in modeling techniques, research techniques, and written and oral communication of mathematical concepts. Prerequisites: 110.202, 550.291, 550.186, 550.310, and 550.361, or permission of instructor.
Goldman, Wierman 4 credits

550.413 (Q,E) 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 will be used in lectures and computer assignments. Intensive use of statistical packages such as S+, SAS, and SPSS, to analyze data. Recommended: familiarity with UNIX operating system.
Wu 4 credits

550.420 (Q,E) 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 550.620. Prerequisite: one year of calculus. Recommended corequisite: 110.202. *Formerly 550.311.*
Fill, Naiman, Wierman 4 credits fall

550.426 (Q,E) 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. Prerequisite: 550.420. *Formerly 550.414.*
Fill, Wierman 4 credits spring

550.430 (Q,E) 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. Prerequisite: 550.420. *Formerly 550.312.*
Naiman, Wu 4 credits spring

550.432 (Q,E) Linear Statistical Models
The general linear model in matrix terms. Techniques of applications, with use of statistical computer packages. Multiple regression, polynomial regression, stepwise regression, multicollinearity, reparametrization, normal correlation models and analysis; basic and multifactor analysis of variances, fixed and random effects. Prerequisites: 550.430 or 550.630; 550.291 or approved alternative. *Formerly 550.422. Last offered fall 1992.*
Naiman, Wu 3 credits

550.433 (Q,E) Statistical Computations
Applications of numerical analysis to statistics. Linear least squares; random number generation; Monte Carlo techniques; analysis of variance; time series computations; numerical integration. Emphasis on computational aspects relevant to practical statistical problems. Prerequisites: 550.430, 550.186. *Formerly 550.423. Last offered spring 1993.*
Naiman 3 credits

550.434 (Q,E) Nonparametric and Robust Methods
Statistical methodology without strict parametric model assumptions. Exploratory data analysis; linear rank statistics; tests of independence, symmetry, location differences, scale differences, and regression alternatives; chi-square and Kolmogorov-Smirnov goodness-of-fit tests; association analysis; order statistics; nonparametric confidence intervals; nonparametric analysis of variance; influence curves; robust estimation of location and regression parameters. Some use of statistical computer programs. Prerequisite: 550.430 or 550.630. *Formerly 550.424. Last offered fall 1994.*
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550.453 (Q,E) Mathematical Game Theory
Mathematical analysis of cooperative and noncooperative games. Theory and solution methods for matrix games (two players, zero-sum payoffs, finite strategy sets), games with a continuum of strategies, N-player games, games in rule-defined form. The roles of information and memory. Selected applications to economic, recreational, and military situations. Prerequisites: 110.202, 550.420, 550.291 or approved alternative. *Last offered spring 1994.*
Goldman 3 credits

550.457 (Q,E) Topics in Operations Research
Study in depth of a special mathematical or computational area of operations research, or a particular application area. Recent topic: decision theory. *Last offered fall 1993.*
Goldman 3 credits

550.460 (Q,E) Optimization Problems and Software
Introduction to useful classes of optimization problems and computer software for their solution. Course emphasizes model formulation and solution by existing computer packages. Intended for engineering and science majors who want to use optimization methodology but are not interested in its theory or algorithmic details. No previous knowledge of optimization is required. Some experience with computing is desirable. Students interested in the theory of optimization should take 550.661-662 instead. *Last offered fall 1994.*
3 credits

550.463 (Q,E) Network Models in Operations Research
In-depth mathematical study of network flow models in operations research, covering theory, algorithms, and applications. Determination of maximum-volume and minimum-cost flows in alternative models; feasibility theorems and combinatorial consequences. Emphasis on linear models and brief discussion of nonlinear models. Prerequisites: 550.361-362 or 550.661. *Last offered spring 1993.*
Hall 3 credits

550.471 (Q,E) Combinatorial Analysis
Counting techniques: generating functions, recurrence relations, Polya's theorem. Combinatorial designs: Latin squares, finite geometries, balanced incomplete block designs. Emphasis on problem solving. Prerequisites: 110.202, 550.191 or approved alternative.
Cowen, Goldman, Scheinerman 4 credits fall

550.472 (Q,E) 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: 110.202, 550.191 or approved alternative.
Cowen, Goldman, Scheinerman 4 credits spring

550.500 Undergraduate Research
Reading, research, or project work for undergraduate students. Arranged individually between students and faculty. Recent topics and activities: percolation models, data analysis, course development assistance. *Offered each semester.*

550.510 Readings in Actuarial Mathematics
Independent reading of mathematical topics pertinent to the insurance industry and actuarial profession. Arranged individually between students and faculty. Possible topics: risk theory, financial mathematics, mathematical demography, survival models.
Wierman

Graduate Courses

550.600 Mathematical Sciences Department Seminar
A variety of topics discussed by speakers from within and outside the University. Required of all resident department graduate students. *Offered each semester.*

550.620 Probability Theory I
Probability as a mathematical discipline, including introductory measure theory. Axiomatic probability, combinatorial probability, random variables, conditional probability, independence, distribution theory, expectation, Lebesgue-Stieltjes integration, variance and moments, probability inequalities, characteristic functions, conditional expectation. Prerequisites: 110.405 and 550.420, or equivalents. *Formerly 550.411.*
Fill, Wierman 4 hours fall

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,