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behavior such as oxidation, corrosion, adsorption and catalysis, environmental effects on mechanical prop-erties and surface control of electronic material properties. Experimental methods used to determine properties of surfaces and interfaces will be illustrated with numerous applications to real systems. Prerequisite: general chemistry and physics or consent of instructor.
Ahearn 3 hours

51.794 Materials Science and Engineering Project
This course is an individually tailored, supervised project that offers the student some research experience through work on a special problem related to his or her field of interest. The research problem can be ad-dressed experimentally or by directed reading. The result of an experimental (or analytical) project must be a written report. The examination of a directed reading project may be written and/or oral at the discretion of the advisor. Scheduled with individual advisors. Prerequisite: It is recommended that all other course work will have been taken prior to this project (or at least completed concurrently with this project). This course is available only to students in the Master of Materials Science and Engineering program.
Staff 3 hours

51.757 Advanced Solid State Physics
A course in the concepts and methods employed in condensed matter physics with applications in materials sci-ence, surface physics, and electronic devices. Topics covered include: atomic and electronic structure of crystalline solids and their role in determining the elastic, transport and magnetic properties of metals, semiconductors and insulators. The effects of structural and chemical disorder on these properties will also be discussed. Prerequisite: 51.345-346 or consent of instructor.
Moorjani 3 hours

51.758 Amorphous Solids
An introductory course on the physics of non-crystalline solids that concerns the effects of topological, compo-sitional and magnetic disorder on the familiar theoretical framework of solid state physics and delineates the influence of disorder on the observed behavior of materials. Topics covered include: preparation and atomic structure of amorphous solids, the importance of short-range order and structural models, percolation and localization and their role in determining the transport, optical and magnetic properties of semiconductors and metals, device applications. Prerequisite: 51.345-346 or consent of instructor.
Moorjani 3 hours

Mathematics

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 soci-ety. A broad undergraduate and graduate curriculum emphasizes four 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; and *Optimization,* the science of determining best or optimal decisions. The curriculum also includes computing, discrete mathematics, numerical analysis, and other important topics in applied mathematics.

Probability and Statistics are treated in the curriculum as a single general area, deal-ing in a unified way with theory and methodology for probabilistic representation of chance phenomena; extraction of important implications of probability models; for-mulation of statistical models; fitting of statistical models to data; interpretation of data. *Operations Research and Optimization* represent a second general area, dealing in unified fashion with the application of optimization theory, mathematical program-ming theory, computer modeling, stochastic modeling, and game theory to problems such as allocation of resources, network flow, optimal facility location, planning and policy, inventory, control of dynamic systems, and approximation of functions. In each of these areas the curriculum is structured through the Ph.D. level. As a third general area, *Computational and Applied Mathematics* covers topics vital or supportive in practice or in advanced study: computing, numerical analysis, advanced matrix analysis, combinatorics, graph theory, 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.

sorption and catalysis, environmental effects on mechanical prop-
erial properties. Experimental methods used to determine properties
d with numerous applications to real systems. Prerequisite: general
ctor.

Project

ipervised project that offers the student some research experience
d to his or her field of interest. The research problem can be ad-
ing. The result of an experimental (or analytical) project must be
cted reading project may be written and/or oral at the discretion of
isors. Prerequisite: It is recommended that all other course work will
at least completed concurrently with this project). This course is
Materials Science and Engineering program.

loyed in condensed matter physics with applications in materials sci-
vices. Topics covered include: atomic and electronic structure of
mining the elastic, transport and magnetic properties of metals,
of structural and chemical disorder on these properties will also be
ent of instructor.

on-crystalline solids that concerns the effects of topological, compo-
iliar theoretical framework of solid state physics and delineates the
avior of materials. Topics covered include: preparation and atomic
ance of short-range order and structural models, percolation and
ie transport, optical and magnetic properties of semiconductors and
1.345-346 or consent of instructor.

SCIENCES

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graduate curriculum emphasizes four branches of
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tistics, the science of making decisions using data;
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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 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 coursework drawing from all areas of the curriculum, along with specialized coursework 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 governmental, industrial, and research organizations.

The undergraduate major in mathematical sciences leads to the B.A. and B.S. degrees. Concentration in computer science or a field of engineering may be included, if desired. 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

Professor Alan F. Karr (Chairman): stochastic processes, probability, approximation theory.

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

Professor Roger A. Horn: analysis, complex variables, matrix analysis.

Professor Eliezer Naddor: operations research, inventory systems, computer methods and applications.

Professor Robert J. Serfling: probability, statistics, asymptotic theory.

Associate Professor John C. Wierman: probability, statistics.

Assistant Professor Jerzy A. Filar: game theory, optimization.

Assistant Professor Robert A. Koyak: mathematical and applied statistics.

Assistant Professor Daniel Q. Naiman: statistics, probability.

Assistant Professor Stephen G. Nash: numerical analysis, optimization, numerical linear algebra.

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

Joint and Visiting Appointments

Professor Rodger D. Parker (Department of Health Services Administration): operations research, combinatorial analysis, dynamic programming.

Professor John P. Young (Department of Health Services Administration): operations research, queueing theory, health systems analysis.

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

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mathematical sciences or related areas, or as a general quantitative education preparatory to a career in business, medicine, or other field. An undergraduate major in mathematical sciences takes an individually tailored program of courses within the department and in the Department of Mathematics (calculus, linear algebra and perhaps further courses such as differential equations, complex variables, analysis, topology and modern algebra) and electives in science and engineering, for example in the Department of Electrical Engineering and 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.

Requirements for the Bachelor's Degree

See also General University Distribution Requirements, pages 44–45.

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.

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 the School of Engineering, respectively. In addition, departmental requirements are:

1) at least 40 credits in courses coded (Q), including a core program consisting of: elementary calculus, advanced calculus, and linear algebra (4 semesters in all); an approved semester course in computing; at least 5 approved departmental 300-level semester courses, including a probability course, a statistics course, and an optimization course.

2) at least 3 semesters of approved coursework in some area of application of the mathematical sciences.

43

Of the 40 credits in (1), at least 18 must be in courses at or above the 300 level. The core program requirements in (1) may be met, for example, by the courses: 11.8, 11.9, 11.12 and 11.13; 55.60; 55.315, 55.316, 55.345, and 2 other approved 300-level departmental courses. The courses in (2) are to constitute a coherent program and at least one must be at or above the 300 level. Appropriate fields include biology, biomedical engineering, biophysics, chemistry, chemical engineering, civil engineering, computer science, earth and planetary sciences, economics, electrical engineering, geography and environmental engineering, materials science and engineering, mechanics, physics, political economy, psychology, social relations, and systems analysis for public decision making.

All courses used to meet these departmental requirements must be passed with grades of C or better.

The requirement of 5 approved 300-level departmental courses is a minimal requirement, allowing maximum flexibility in planning degree programs. However, 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 an additional course in optimization (55.346), a course in stochastic processes (55.329), courses in discrete mathematics (55.48; 55.349, 55.350), a course in com-

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ed areas, or as a general quantitative education
s, medicine, or other field. An undergraduate major
n individually tailored program of courses within the
nt of Mathematics (calculus, linear algebra and per-
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ring and Computer Science (operating systems, digi-
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n, and supplemental information, may be obtained

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requirements below. A written copy of the program
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puting algorithms (55.362), and a course in numerical methods (55.364). Further courses of general interest are 55.300, 55.318, 55.319, and 55.357-358. (At a more advanced level, the courses 55.301, 55.303, 55.304, 55.341, 55.342, 55.344, 55.365-.366 and 55.375 may be considered; these courses require 11.305 as a pre- or co-requisite.)

The department also encourages its majors to obtain at least a reading knowledge of French, German, or Russian. Students anticipating graduate work in the mathematical sciences should be aware that competence in one or more of these languages 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, and optimization, advanced study is possible also in graph theory, numerical analysis, matrix analysis, and complex analysis, as well as interdisciplinary topics in cooperation with other departments, particularly the Departments of Biostatistics, Electrical Engineering and Computer Science, Geography and Environmental Engineering, Health Services Administration, Mathematics, Political Economy, and Sociology. A graduate student in the Department of Mathematical Sciences may thus develop a program that suits his or her individual interests and objectives.

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

Admission Requirements

To be admitted to an advanced degree program in the department, a candidate must show that he or 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 candidate's credentials; there are no rigid requirements.

A candidate should submit transcripts of previous academic work, letters of recommendation from persons qualified to evaluate his or her academic performance and potential for graduate study, a letter describing anticipated professional goals, and Graduate Record Examinaton (GRE) scores. The department prefers to receive the score of the GRE advanced test in mathematics, but will also accept the score of the advanced test in the candidate's undergraduate major.

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. The M.A. degree entails a foreign language requirement, which can be satisfied by completing at a satisfactory level the Graduate Student Foreign Language Test in French, German, or Russian.

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To obtain departmental certification for the master's degree, the student must:

1) Complete satisfactorily at least 8 one-semester courses of graduate work in a coherent program approved by the faculty adviser. All 600-level courses and many 300-level courses in the department are satisfactory for this requirement.

2) Meet *one* of the following three options:

a) Pass one of the three 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;

c) Complete satisfactorily 2 additional one-semester graduate courses, as approved by the faculty adviser.

3) Demonstrate a working knowledge of the utilization of computers in the mathematical sciences.

All courses in the master's program must be passed with grades of B or better.

In consultation with the faculty adviser, a candidate for the master's degree plans a complete program of proposed coursework 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.

Combined 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 the end of the sophomore 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, and 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 coursework 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 and significant contribution to knowledge in the mathematical sciences.

Course Requirements 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.

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1. Basic Courses. All students are expected to master introductory material in probability (55.341), statistics (55.344) or stochastic processes (55.342), optimization (55.303), operations research (55.351 or 55.357), matrix analysis (55.301), and computational and applied mathematics (55.362, 55.365, 55.349, 55.350). Normally, a student will have completed at least eight basic courses by the end of the fourth semester of residence.

2. Specialized Courses. Each student takes advanced courses appropriate to the proposed area of dissertation research. Sample programs in areas such as probability, statistics, 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.

3. 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 coursework, 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 coursework 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-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 coursework 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 three written parts, covering the topic areas: I. Probability and Statistics, II. Operations Research and Optimization, and III. Computational and Applied Mathematics. The student must pass two of the written parts.

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 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: demonstration of ability to read scientific material in French, German, or Russian; acquisition of teaching experience under faculty supervision; demonstration of a working knowledge of the use of computers in the mathematical sciences; passing of the University's Graduate Board examination. The Graduate Board examination covers specialized and elective coursework and prospective dissertation research. It is normally taken in the third year of residence, shortly after a departmental examination taken as preparation.

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

Facilities

The department is located in Maryland Hall. Office space and liberal access to microcomputers and terminals for time-shared computing are provided to resident graduate students. A 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.

Financial Assistance

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.

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.

Probability and Statistics

55.11-12 (Q,E) Statistical Analysis
A general survey of statistical methodology. Fall semester: 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. Spring semester: 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. Three lectures and a conference weekly. Some use of computer terminals and the MINITAB statistical package, but prior computing experience not required. Students who may wish to undertake more than two semesters of probability and statistics should consider 55.315-316 or 55.341-344. Not open to mathematical sciences majors, who should take 55.315-316 instead. Prerequisite: four years of high school mathematics; 55.11 required for continuation to 55.12.
4 credits

55.315 (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 55.341. Prerequisites: one year of calculus; coregistration in 11.12 recommended.
4 credits   Offered fall semester

55.316 (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: 55.315.
4 credits   Offered spring semester

55.323 (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: 55.316, 55.60.
3 credits

am is available from the department

Office space and liberal access to
computing are provided to resident
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ssical and robust estimation of location, con-
ductory analysis of variance, introductory non-
on analysis, correlation, further nonparametric
, Bayesian inference, time series, simultaneous
e weekly. Some use of computer terminals and
ence not required. Students who may wish to
should consider 55.315-316 or 55.341-344. Not
-316 instead. Prerequisite: four years of high

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ta analysis. Emphasis on techniques of applica-
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res; random number generation; Monte Carlo
erical integration. Emphasis on computational
5.316, 55.60.

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55.329 (Q,E) Introduction to Stochastic Processes
Models of phenomena evolving in time or space according to probabilistic laws. Computational, distributional, and asymptotic properties of random walks, Markov chains, Poisson processes, birth-death processes, Brownian motion, and stationary processes. Selected applications in the sciences and engineering, with attention to model formulation, underlying assumptions, and extraction of informative results from the model. Prerequisite: 55.315; corequisite: 11.13.
3 credits Offered fall semester

55.332 (Q,E) Linear Statistical Models
The general linear model in matrix terms. Techniques of application, with use of statistical computer packages. Multiple regression, polynomial regression, stepwise regression, multicollinearity, reparametrization, normal correlation models and analysis; basic and multifactor analysis of variance, fixed and random effects. Prerequisites: 55.316 or 55.344; 11.13.
3 credits

55.333 (Q,E) Design of Experiments
Experimental design principles and applications. Completely randomized, complete block, nested and nested factorial, split plot, Latin square, factorial, and balanced and partially balanced incomplete block designs; multiple comparisons; confounding; fractional replications; transformations; analysis of covariance; response surface exploration. Prerequisite: 55.332.
3 credits

55.334 (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: 55.316 or 55.344.
3 credits

55.338 (Q,E) Survey Sampling
Sample survey theory and design. Simple random, stratified, systematic, cluster, and pps sampling; estimation of population means, variances, ratios; ratio-, difference-, and regression-type estimators; use of auxiliary information; confidence intervals; optimum choice of sample size, stratum allocations, selection probabilities; double sampling and repetitive surveys; nonsampling errors; randomized response; sufficiency principle in sample survey models; superpopulation models. Prerequisite: 55.316 or 55.344.
3 credits

55.341 (Q,E) Probability Theory
Probability theory as a mathematical discipline, at the level of elementary real analysis. Axiomatic probability, random variables, combinatorial probability, independence, single- and multi-variable distribution theory, expectation, convergence of sequences of random variables, characteristic functions, inequalities, limit theorems for sums of independent random variables, conditional expectation, introduction to martingales. Prerequisite: 11.12-13; corequisite: 11.305.
4 credits Offered fall semester

55.342 (Q,E) Stochastic Processes I
Mathematical theory of the basic stochastic processes. Dependence relations, structural properties, sample path behavior and asymptotic properties of random walks, Poisson processes, Markov chains, and continuous time Markov processes with countable state space. Applications that illuminate the theory. Prerequisite: 55.341.
4 credits Offered spring semester

55.344 (Q,E) Statistical Theory
The fundamentals of mathematical statistics. Distribution theory for statistics of normal samples; exponential statistical models; sufficiency principle; least squares, maximum likelihood and UMVU estimation; hypothesis testing, the Neyman-Pearson lemma, likelihood ratio procedures; the general linear model, the Gauss-Markov theorem, multiple comparisons; contingency tables, chi-square methods, goodness-of-fit; nonparametric and robust methods; decision theory, Bayes and minimax procedures. Prerequisite: 55.341.
4 credits Offered spring semester

55.393-394 (Q,E) Topics in Probability and Statistics
Study in depth of a special area. Possible topics: martingales and optimal stopping, Markov renewal theory, reliability theory and analysis, time series analysis, applied multivariate statistical theory.

55.651 Statistical Inference
Advanced concepts and tools fundamental to research in mathematical statistics and statistical inference: asymptotic theory; optimality; various mathematical foundations. Prerequisite: 55.344.
3 hours weekly Offered fall semester

55.654 Multivariate Statistical Theory
Theory of statistics when data are in the form of multivariate observations. The multivariate normal distribution; Wishart distributions; inference on means, Hotelling's T^2; multivariate linear models; regression, ANOVA; inference on covariances; classification and discrimination; principal components; canonical correlations; canonical variables. Prerequisites: 55.301, 55.344.
3 hours weekly

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55.655 Time Series Analysis
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: 55.301, 55.344.
3 hours weekly

55.656 Sequential Analysis
Theory of statistics when the sample size is random. Curtailed binomial sampling; Wald's sequential probability ratio test; operating characteristics, sample size, and optimal properties; Cox's theorem and sequential t-, χ^2- and T^2-tests; Bayes and minimax sequential decision problems; sequential estimation of regression functions; Stein's double sampling plan; bounded length confidence intervals; selection procedures; sequential design of experiments. Prerequisite: 55.344.
3 hours weekly

55.657 Nonparametric and Robust Inference
Distribution-free statistics; asymptotic relative efficiency of tests; U-statistics; linear rank statistics; one-sample, two-sample, and general regression problems; concepts of robust and adaptive estimation; M-, L-, and R-estimates; nonparametric density estimation. Prerequisite: 55.344.
3 hours weekly

55.658-659 Advanced Topics in Statistics
Advanced topics chosen according to the interests of the instructor and students. Possible topics: large sample statistical theory, contingency table analysis; reliability theory, optimization methods in statistics, foundations of statistics, nonparametric density and regression estimation, limit theory of empirical stochastic processes.

55.662 Advanced Probability
Probability at the level of measure theory. Probability measures, random variables, expectation, independence, convergence of sequences of random variables, characteristic functions, inequalities, classical limit theorems, conditional expectation and conditional independence, histories and stopping times, martingales, interchangeability, infinite divisibility, stationary processes and ergodic theory, stochastic processes. Prerequisites: 55.341 and 11.605.
4 hours weekly

55.664 Stochastic Processes II
Continuation of 55.342. Theory of renewal processes, Markov renewal processes, semi-Markov processes, regenerative and semi-regenerative processes, stationary processes, and Brownian motion. Structure, sample path behavior and asymptotic properties. Prerequisites: 55.301, 55.342.
3 hours weekly   Offered fall semester

55.668-669 Advanced Topics in Probability and Stochastic Processes
Advanced topics chosen according to the interests of the instructor and students. Possible topics: Brownian motion and potential theory, diffusion processes, point processes and random measures, inference for stochastic processes, invariance principles for sums of dependent random elements.

Operations Research and Optimization

55.303 (Q,E) Foundations of Optimization
Study of the fundamental theory underlying linear and nonlinear optimization. Unconstrained optimization, constrained optimization, saddlepoint conditions, Kuhn-Tucker conditions, linear programming, the simplex algorithm, post-optimality, duality, convexity, quadratic programming. Prerequisite: 11.12-13; corequisite: 11.305.
4 credits   Offered fall semester

55.304 (Q,E) Optimization Algorithms
Design and analysis of algorithms for linear and nonlinear optimization. The revised simplex method, the primal-dual algorithm, algorithms for network problems, first- and second-order methods for nonlinear problems, quadratic programming techniques, and methods for constrained nonlinear problems. Prerequisite: 55.303.
4 credits   Offered spring semester

55.307 (Q,E) Introduction to Game Theory
Introduction to a spectrum of decision problems involving competing interests and their analysis using basic game-theoretic concepts and techniques. Applications from economic, military and recreational contexts. Solution of numerical problems using available computer programs. Emphasis on conceptual understanding and problem solving rather than mathematical theory; students wishing to explore the mathematical bases of game theory should consider 55.369. Prerequisites: 11.12-13, 55.315.
3 credits

55.318 (Q,E) Queueing Systems
Introduction to description and analysis of systems involving waiting lines. Transient and steady-state behavior of queue length, waiting time and busy period processes for the fundamental single-server queueing systems. Variations such as multiple servers, finite waiting rooms, and customers of differing priorities. Possible additional topics include statistical analysis of queues, optimization of queueing systems, and networks of queues. Applications in engineering, health-care delivery, demography, and other areas. Case studies and projects. Prerequisite: 55.329 or 55.342.
3 credits   Offered spring semester

55.339 (Q,E) Operations Research Applications of Markov Processes
Case studies in applications of Markov process theory to operations research problems. Review of analytical methods needed (for example, from the theory of semi-Markov processes). Applications introduced through

approaches. Descriptive techniques; regression
correlation; stationary processes; spectral analysis

binomial sampling; Wald's sequential probability
l properties; Cox's theorem and sequential t-, F
ms; sequential estimation of regression functions;
tervals; selection procedures; sequential design of

sts; U-statistics; linear rank statistics; one-sample,
robust and adaptive estimation; M-, L-, and R-
.344.

tructor and students. Possible topics: large sample
, optimization methods in statistics, foundations of
imit theory of empirical stochastic processes.

res, random variables, expectation, independence,
ic functions, inequalities, classical limit theorems,
histories and stopping times, martingales, inter-
ergodic theory, stochastic processes. Prerequisites:

arkov renewal processes, semi-Markov processes,
rocesses, and Brownian motion. Structure, sample
301, 55.342.

Processes
tructor and students. Possible topics: Brownian mo-
sses and random measures, inference for stochastic
lom elements.

onlinear optimization. Unconstrained optimization,
ucker conditions, linear programming, the simplex
gramming. Prerequisite: 11.12-13; corequisite: 11.305.

ear optimization. The revised simplex method, the
first- and second-order methods for nonlinear prob-
for constrained nonlinear problems. Prerequisite:

g competing interests and their analysis using basic
m economic, military and recreational contexts. Solu-
grams. Emphasis on conceptual understanding and
ts wishing to explore the mathematical bases of game
.315.

ing waiting lines. Transient and steady-state behavior
for the fundamental single-server queueing systems.
, and customers of differing priorities. Possible addi-
zation of queueing systems, and networks of queues.
aphy, and other areas. Case studies and projects. Pre-

ov Processes
o operations research problems. Review of analytical
Markov processes). Applications introduced through

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journal articles on such topics as reliability and maintainability of equipment, birth control and health services planning models, skip-lot testing in quality control, computer-aided medical diagnosis, war-gaming approaches in strategic defense analysis, demographic forecasting, optimal fault location, quality assurance in drug testing. Prerequisites: 11.13; 55.329 or 55.342.
3 credits

55.345-346 (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. Appropriate for undergraduate and graduate students without the mathematical background required for 55.303; students anticipating extended work in optimization should consider 55.303. Prerequisites: 11.8-9; 55.60. Prerequisites for continuation to second semester: 11.12, 11.13.
4 credits

55.351 (Q,E) Inventory Systems
Methodology and art of building and analyzing models as applied to inventory systems. Theoretical and quantitative approach to problems of balancing carrying costs, shortage costs, and replenishing costs. Optimal decision rules for "when to replenish" and "by how much." Deterministic and probabilistic demand, zero and nonzero leadtime, price discounts, multi-item systems, equivalence of systems, choice of optimal policies, heuristic decisions. Application of sensitivity analysis, simulation, mathematical programming, Markov chains. Students design, implement, check out, and document several computer programs. Prerequisite: 55.60; corequisite: 55.315.
3 credits

55.357-358 (Q,E) Modeling for Decisions in Operations Research and Management Science
Methodology and art of constructing decision models in business, government, industry and nonprofit organizations. Formulation of mathematical and simulation models of systems involving allocation of resources, inventory, waiting lines, and competition. Analysis using optimization methods and computer programs. Students design, implement, check out, and document several computer programs. Prerequisite: 55.60; for continuation to second semester, 55.315.
3 credits

55.369 (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: 11.12-13, 55.315.
3 credits

55.395-396 (Q,E) Topics in Operations Research
Study in depth of a special mathematical or computational area of operations research, or a particular application area. Possible topics: information system design, simulation methodology, production planning, health systems analysis, and mathematical methods of transportation science.

55.397-398 (Q,E) Topics in Optimization
Study in depth of a special area of mathematical optimization theory, or a significant application context. Possible topics: mathematics of optimal control, decision theory, convex geometry in optimization, quadratic programming, optimal facility location and layout, and optimal network design.

55.609 Advanced Linear Programming
Further theory and application of optimizing a linear function subject to linear constraints. An advanced algorithmic topic (for example, the recent ellipsoid method) and an advanced modeling or application topic (for example, the use of linear programming in treating Markov decision chains) are studied in depth. Prerequisite: 55.303.
3 hours weekly

55.610 Advanced Nonlinear Programming
Theory and application of optimizing a nonlinear function subject to linear or nonlinear constraints. Duality theory, convex analysis and nonlinear sensitivity analysis; applications of these techniques to special classes of problems such as geometric programs and location problems. Prerequisites: 11.305, 55.303.
3 hours weekly

55.614 Optimization of Functionals
Examination from a unified point of view of topics in infinite-dimensional optimization such as the calculus of variations, optimal control theory, and approximation theory. Applications in the physical sciences, engineering, and statistics. Prerequisites: 11.305, 55.303.
3 hours weekly

55.631 Numerical Methods for Optimization
Advanced topics in the design and analysis of numerical methods for solving optimization problems. Algorithms include gradient methods, conjugate direction techniques, quasi-Newton methods, feasible direction methods, and successive quadratic programming. Issues of matrix factorization and updating, data storage, line searches, convergence, efficiency, and numerical stability. Prerequisites: 55.304, 55.365.
3 hours weekly

55.641 Advanced Topics in Inventory and Production
Analysis and synthesis of probabilistic reorder-point inventory systems and multi-item multi-level production

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systems. Application of Markov chains, renewal processes, elementary integral equations, optimal and heuristic decision rules, information retrieval, and computer implementations. Prerequisite: 55.351.

55.691-692 Advanced Topics in Optimization

Advanced topics chosen according to the interests of the instructor and students. Possible topics: dynamic programming, integer programming, game theory, stochastic programming, advanced network flow theory, matching theory, and matroid optimization problems.

55.693-694 Advanced Topics in Operations Research

Advanced topics chosen according to the interests of the instructor and students. Possible topics: sequencing and scheduling theory, utility theory, advanced decision analysis, resource management modeling, and queueing network analysis, probabilistic analysis of algorithms.

Computational and Applied Mathematics

55.48 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.
3 credits Offered spring semester

55.60 (Q,E) Introduction to Computing Applications

Introduction to the uses of computers. Creation and editing of files. Text processing. Information storage and retrieval. Computer program libraries. Modeling of deterministic and probabilistic systems. Statistical computing. Analysis of algorithms. Programming in BASIC and FORTRAN. Students use computer terminals in weekly assignments. Emphasis on learning to use computer resources as part of the process of formulating and solving real problems rather than on theoretical issues. Previous experience with computing or programming not required. Prerequisite: 4 years of high school mathematics.
3 credits Offered fall semester

55.64 Software Engineering Workshop

Directed project workshop to develop microcomputer software for mathematical sciences applications. Students prepare detailed proposals for projects with consent of the instructor and code, debug, refine, test, document, and present working programs. Prerequisite: 55.60 or equivalent.
3 credits

55.300 (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: 11.12-13, 55.60, 55.315-316, and 55.345, or equivalents, or instructor's permission.
4 credits.

55.301 (Q,E) Matrix Analysis and Linear Algebra

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 non-negative matrices, generalized inverses. Prerequisites: 11.12-13, 11.305.
4 credits Offered spring semester

55.319 (Q,E) Dynamic Systems

Theory and applications of multivariable dynamic systems. State-space formulation, linear systems, fundamental solution sets, equilibrium properties, positive systems, optimal control theory, analysis of nonlinear systems. Models of population growth and interactions, economic dynamics, and engineering systems. The mathematical tools are essentially a combination of differential (or difference) equations and linear algebra. Prerequisites: 11.12-13, 11.302 or equivalent.
3 credits Offered spring semester

55.323 (Q,E) Statistical Computations

(See listing under "Probability and Statistics.")

55.349 (Q,E) Combinatorial Analysis

Counting techniques: generating functions, recurrence relations, Pólya's theorem. Combinatorial designs: Latin squares, finite geometries, balanced incomplete block designs. Emphasis on problem solving. Prerequisites: 11.12-13.
3 credits Offered fall semester

55.350 (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: 11.12-13.
3 credits Offered spring semester

55.362 (Q,E) Computer Algorithms for the Mathematical Sciences

Design and analysis of computer algorithms frequently encountered in the mathematical sciences. Algorithms include greedy methods, dynamic programming, backtracking, and branch and bound, with emphasis on com-

ıtary integral equations, optimal and heuristic
ons. Prerequisite: 55.351.

or and students. Possible topics: dynamic pro-
amming, advanced network flow theory, match-

tor and students. Possible topics: sequencing
resource management modeling, and queue-

ı algebra; induction and recursion; sets, func-
ry combinatorics; modular arithmetic and the
groups; graph theory. Selected applications
and construct proofs will be part of the course.

;. Text processing. Information storage and re-
and probabilistic systems. Statistical comput-
ɪN. Students use computer terminals in weekly
part of the process of formulating and solving
ence with computing or programming not re-

: mathematical sciences applications. Students
ctor and code, debug, refine, test, document,

atical models. Synthesis of ideas, techniques,
;. Case studies to illustrate basic features of the
odeling techniques, research techniques, and
erequisites: 11.12-13, 55.60, 55.315-316, and

ful in analysis, economics, statistics, control
nposition and factorization theorems, positive
eorems, variational methods, positive and non-
.1.305.

-space formulation, linear systems, fundamen-
l control theory, analysis of nonlinear systems,
s, and engineering systems. The mathematical
) equations and linear algebra. Prerequisites:

Pólya's theorem. Combinatorial designs: Latin
hasis on problem solving. Prerequisites: 11.12-13.

Theory of adjacency, connectivity, traversabil-
nt in engineering and the sciences. Topics in-
Euler and Hamilton; design of graphs realizing
rected toward problem solving, algorithms and
requisites: 11.12-13.

es
ered in the mathematical sciences. Algorithms
nd branch and bound, with emphasis on com-

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puter solution of discrete optimization problems. Analysis of design includes generation of random test data, and theoretical and experimental estimates of computing times. Prerequisites: 55.60, 55.315.
4 credits Offered spring semester

55.364 (Q,E) Numerical Methods in Computing
Survey of current numerical methods for solving linear algebraic equations, approximating continuous functions, computing definite integrals, solving ordinary differential equations, solving nonlinear equations, minimizing continuous functions, and solving least squares problems. Emphasis on finding and using good algorithms. Students use subroutines available on the University's computer system. Computer laboratory.
Prerequisites: 11.8-9, 11.13, 55.60.
4 credits Offered fall semester

55.365-366 (Q,E) Numerical Analysis
General tools and techniques for numerical solution of mathematical problems and analysis of solution algorithms. Computational linear algebra; data fitting and function approximation; numerical integration and differentiation; solution of nonlinear equations and systems of equations; difference and differential equations.
Prerequisites: 55.60, 11.12-13; corequisite: 11.305; first semester prerequisite to the second.
4 credits

55.375 Functional Analysis and Applications
Theory of functional analysis relevant to applications in optimization, probability/statistics, control and system theory, and partial differential equations. Hilbert spaces: projections, orthogonality, representation of linear functionals; Banach spaces: linear operators, Hahn-Banach and closed graph theorems, uniform boundedness principle; convexity: support and Minkowski functionals; extreme points. Applications to selected topics such as calculus in Banach spaces, Fourier series, approximation theory, optimization of functionals, distributions and differential equations. Prerequisites: 11.305, linear algebra.
4 credits Offered fall semester

55.391-392 (Q,E) Topics in Computational and Applied Mathematics
Possible topics: applications of modern algebra; simulation methods.

55.638-639 Advanced Topics in Applied Mathematics
Possible topics: numerical techniques for least squares problems; algorithms for nonlinear least squares problems; combinatorial algorithms; extremal graph theory; sparse matrix computations; eigenvalue/eigenvector problems, approximation theory.

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55.72 (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. Preference given to freshmen.
Prerequisites: 55.60; 11.8.
1 credit Offered spring semester

55.399 (Q,E) Undergraduate Research and Special Studies
Reading, research, or project work for undergraduate students as arranged individually between students and faculty.
Offered both semesters

55.600 Mathematical Sciences Department Seminar
A variety of topics discussed by speakers from within and outside the University. Required of all resident department graduate students.
1 hour weekly Offered both semesters

55.699 Special Studies and Research
Reading, research, or project work for graduate students as arranged individually between students and faculty.
Offered both semesters

MECHANICAL ENGINEERING

The Department of Mechanical Engineering offers graduate and postdoctoral programs of instruction and research. Undergraduate programs are offered in engineering mechanics and in mechanical engineering. Mechanical engineering is a broad field which deals with the conversion of energy through useful mechanical devices. The breadth of interests is reflected in the two main stems of the undergraduate curriculum—thermal systems and mechanical systems. Engineering mechanics is an area of study closely related to mechanical engineering, but with increased emphasis on basic sciences and modern mathematical analysis. The breadth of these two programs and