Department of Mathematical Sciences Courses

About Course Numbers:
Each Carnegie Mellon course number begins with a two-digit prefix that designates the department offering the course (i.e., 76-xxx courses are offered by the Department of English). Although each department maintains its own course numbering practices, typically, the first digit after the prefix indicates the class level: xx-1xx courses are freshmen-level, xx-2xx courses are sophomore level, etc. Depending on the department, xx-6xx courses may be either undergraduate senior-level or graduate-level, and xx-7xx courses and higher are graduate-level. Consult the Schedule of Classes (https://enr-apps.as.cmu.edu/open/SOC/SOCServlet/) each semester for course offerings and for any necessary pre-requisites or co-requisites.

21-101 Freshman Mathematics Seminar
Intermittent: 3 units
This course is offered in the Fall semester for first semester Freshmen interested in majoring in mathematics. Topics vary from year to year. Recent topics have included Fermat's last theorem, finite difference equations, convexity, and fractals. (Three 50 minute lectures)

21-105 Pre-Calculus
Summer: 9 units
Review of basic concepts, logarithms, functions and graphs, inequalities, polynomial functions, complex numbers, and trigonometric functions and identities. Special summer program only. 3 hrs lec., 1 hr.rec.

21-111 Differential Calculus
Fall and Spring: 10 units
Review of basic algebra, functions, limits, derivatives of algebraic, exponential and logarithmic functions, curve sketching, maximum-minimum problems. Successful completion of 21-111 and 21-112 entitles a student to enroll in any mathematics course for which 21-120 is a prerequisite. (Three 50 minute lectures, two 50 minute recitations)

21-112 Integral Calculus
Fall and Spring: 10 units
Definite and indefinite integrals, and hyperbolic functions; applications of integration, integration by substitution and by parts. Successful completion of 21-111 and 21-112 entitles a student to enroll in any mathematics course for which 21-120 is a prerequisite. (Three 50 minute lectures, two 50 minute recitations) Prerequisite: 21-111

21-115 Basic Differential Calculus
Summer: 5 units
Functions, limits, derivatives, curve sketching, Mean Value Theorem, trigonometric functions, related rates, linear and quadratic approximations, maximum-minimum problems. Special summer program only.

21-120 Differential and Integral Calculus
All Semesters: 10 units
Functions, limits, derivatives, logarithmic, exponential, and trigonometric functions, inverse functions, definite and indefinite integrals, and hyperbolic functions; applications of integration, integration by substitution and by parts. (Three 50 minute lectures, two 50 minute recitations)

21-122 Integration and Approximation
All Semesters: 10 units
Integration by trigonometric substitution and partial fractions; arclength; improper integrals; Simpson’s and Trapezoidal Rules for numerical integration; separable differential equations, Newton’s method, Euler’s method, Taylor’s Theorem including a discussion of the remainder, sequences, series, power series. Parametric curves, polar coordinates, vectors, dot product. (Three 50 minute lectures, two 50 minute recitations) Prerequisites: 21-112 or 21-120

21-124 Calculus II for Biologists and Chemists
Spring: 10 units
This is intended as a second calculus course for biology and chemistry majors. It uses a variety of computational techniques based around the use of MATLAB or a similar system. Topics to be covered include: Integration: techniques and numerical integration. Ordinary differential equations: techniques for solving ODEs and numerical methods. Modeling with ODEs (e.g., infection, population models). Linear algebra: matrices, complex numbers, eigenvalues, eigenvectors. Systems of ordinary differential equations (if time allows: stability of differential systems). Probability: discrete and continnum probability, conditional probability and independence, limit theorems, important distributions, probabilistic models. (Three 50 minute lectures, two 50 minute recitations) Prerequisites: 21-111 or 21-120

21-127 Concepts of Mathematics
All Semesters: 10 units
This course introduces the basic concepts, ideas and tools involved in doing mathematics. As such, its main focus is on presenting informal logic, and the methods of mathematical proof. These subjects are closely related to the application of mathematics in many areas, particularly computer science. Topics discussed include a basic introduction to elementary number theory, induction, the algebra of sets, relations, equivalence relations, congruences, partitions, and functions, including injections, surjections, and bijections. A basic introduction to the real numbers, rational and irrational numbers. Supremum and infimum of a set. (Three 50 minute lectures, two 50 minute recitations)

21-128 Mathematical Concepts and Proofs
Fall: 12 units
This course is intended for MCS first-semester students who are interested in pursuing a major in mathematical sciences. The course introduces the basic concepts, ideas and tools involved in doing mathematics. As such, its main focus is on presenting informal logic, and the methods of mathematical proof. These subjects are closely related to the application of mathematics in many areas, particularly computer science. Topics discussed include a basic introduction to elementary number theory, induction, the algebra of sets, relations, equivalence relations, congruences, partitions, and functions, including injections, surjections, and bijections. A basic introduction to the real numbers, rational and irrational numbers. Supremum and infimum of a set. (Three 50 minute lectures, two 50 minute recitations)

21-201 Undergraduate Colloquium
Fall and Spring: 1 unit
All mathematics majors meet each week to hear discussions on current research by faculty or students, presentations on mathematics from mathematicians outside academia, and expository talks on selected mathematical topics not part of the usual curricula. Also will include topics of special interest to undergraduates such as preparation for graduate school. (One 50 minute session)

21-228 Discrete Mathematics
Fall and Spring: 9 units
The techniques of discrete mathematics arise in every application of mathematics, which is not purely continuous, for example in computer science, economics, and general problems of optimization. This course introduces two of the fundamental areas of discrete mathematics: enumeration and graph theory. The introduction to enumeration includes permutations, combinations, and topics such as discrete probability, combinatorial distributions, recurrence relations, generating functions, Ramsey’s Theorem, and the principle of inclusion and exclusion. The introduction to graph theory includes topics such as paths, walks, connectivity, Eulerian and Hamilton cycles, planar graphs, Euler’s Theorem, graph coloring, matchings, networks, and trees. (Three 50 minute lectures, one 50 minute recitation) Prerequisites: 21-127 or 15-151 or 21-128
21-235 Mathematical Studies Analysis I  
Fall: 12 units  
A component of the honors program, 21-235 is a more demanding version of 21-355 of greater scope. Topics to be covered typically include: metric spaces, normed spaces, and inner product spaces; further properties of metric spaces such as completions, density, compactness, and connectedness; limits and continuity of maps between metric spaces, homeomorphisms, extension theorems, contraction mappings, extreme and intermediate value theorems; convergence of sequences and series of functions; metric spaces of functions, sequences, and metric subsets; Stone-Weierstrass and Arzela-Ascoli theorems; Baire category and applications; infinite series in normed spaces, convergence tests, and power series; differential calculus of maps between normed spaces; inverse and implicit function theorems in Banach spaces; existence results in ordinary differential equations. The prerequisite sequence 21-128, 21-242, 21-269 is particularly recommended. (Three 50 minute lectures, one 50 minute recitation)  
Prerequisites: (21-127 or 15-151 or 21-128) and (21-268 or 21-269) and (21-242 or 21-241)  

21-236 Mathematical Studies Analysis II  
Spring: 12 units  
A component of the honors program, 21-236 is a more demanding version of 21-356 of greater scope. Topics to be covered typically include: Lebesgue measure in Euclidean space, measurable functions, the Lebesgue integral, integral limit theorems, Fubini-Tonelli theorem, and change of variables; Lebesgue spaces, completeness, approximation, and embeddings; absolutely continuous functions, functions of bounded variation, and curve lengths; differentiable submanifolds of Euclidean space, tangent spaces, mappings between manifolds, vector and tensor fields, manifolds with boundary and orientations; differential forms, integration of forms, Stokes' theorem; Hausdorff measure, divergence theorem. (Three 50 minute lectures, one 50 minute recitation)  
Prerequisite: 21-235 Min. grade B  

21-237 Mathematical Studies Algebra I  
Fall: 12 units  
A component of the honors program, 21-237 is a more demanding version of 21-373 (Algebraic Structures) of greater scope. Abstract algebra is the study of algebraic systems by the axiomatic method, and it is one of the core areas of modern mathematics. This course is a rigorous and fast-paced introduction to the basic objects in abstract algebra, focusing on groups and rings. Group-theoretic topics to be covered include: homomorphisms, subgroups, cosets, Lagrange's theorem, conjugation, normal subgroups, quotient groups, isomorphism theorems, automorphism groups, characteristic subgroups, group actions, Cauchy's theorem, Sylow's theorem, normalisers, centralisers, class equation, finite p-groups, permutation and alternating groups, direct and semidirect products, simple groups, subnormal series, the Jordan-Hölder theorem. Ring-theoretic topics include: subrings, ideals, quotient rings, isomorphism theorems, polynomial rings, Zorn's Lemma, prime and maximal ideals, prime and irreducible elements, factorization, PID's and UFD's, Noetherian domains, the Hilbert Basis Theorem, Gauss' lemma and the Eisenstein criterion for irreducibility, fields of fractions, properties of polynomial rings over fields and UFD's, finite fields and applications. The prerequisite sequence 21-128, 21-242, 21-269 is particularly recommended. (Three 50 minute lectures, one 50 minute recitation)  
Prerequisites: (21-127 or 15-151 or 21-128) and (21-268 or 21-269) and (21-242 or 21-241)  

21-238 Mathematical Studies Algebra II  
Spring: 12 units  
A component of the honors program, 21-238 is a more demanding version of 21-341 (Linear Algebra) of greater scope. Linear algebra is a crucial tool in pure and applied mathematics. This course aims to introduce the main ideas at a high level of rigour and generality. The course covers vector spaces over arbitrary fields and the natural generalization to modules over rings. Vector space topics to be covered include: fields, Zorn's Lemma, vector spaces (possibly infinite dimensional) over an arbitrary field, independent sets, bases, existence of a basis, exchange lemma, dimension. Linear transformations, dual space, multilinear maps, tensor products, exterior powers, the determinant, eigenvalues, eigenvectors, characteristic and minimal polynomial of a transformation, the Cayley-Hamilton theorem. Module-theoretic topics to be covered include: review of (commutative) rings, R-modules, sums and quotients of modules, free modules, the structure theorem for finitely generated modules over a PID, Jordan and rational canonical forms, structure theory of finitely generated abelian groups. Further topics in real and complex inner product spaces include: orthonormal sets, orthonormal bases, the Gram-Schmidt process, symmetric/hermitian operators, orthogonal/unitary operators, the spectral theorem, quadratic forms, the singular value decomposition. Possible additional topics: applications to combinatorics, category theory, representations of finite groups, unitary representations of infinite groups. (Three 50 minute lectures, one 50 minute recitation)  
Prerequisite: 21-237 Min. grade B  

21-240 Matrix Algebra with Applications  
Fall and Spring: 10 units  
Vectors and matrices, the solution of linear systems of equations, vector spaces and subspaces, orthogonality, determinants, real and complex eigenvalues and eigenvectors, linear transformations. The course is intended for students in Economics, Statistics, Information Systems, and it will focus on topics relevant to these fields. (Three 50 minute lectures, one 50 minute recitation)  

21-241 Matrices and Linear Transformations  
All Semesters: 10 units  
A first course in linear algebra intended for scientists, engineers, mathematicians and computer scientists. Students will be required to write some straightforward proofs. Topics to be covered: vectors and matrices, rowspace and columnspace of a matrix, rank and nullity, solving linear systems by row reduction of a matrix, inverse matrices and determinants, change of basis, linear transformations, inner product of vectors, orthonormal bases and the Gram-Schmidt process, eigenvectors and eigenvalues, diagonalization of a matrix, symmetric and orthogonal matrices. 21-127 is strongly recommended. (Three 50 minute lectures, one 50 minute recitation)  

21-242 Matrix Theory  
Fall: 10 units  
A component of the honors program, 21-242 is a more demanding version of 21-241 (Matrix Algebra and Linear Transformations), of greater scope, with increased emphasis placed on rigorous proofs. Topics to be covered: complex numbers, real and complex vectors and matrices, rowspace and columnspace of a matrix, rank and nullity, solving linear systems by row reduction of a matrix, inverse matrices and determinants, change of basis, linear transformations, inner product of vectors, orthonormal bases and the Gram-Schmidt process, eigenvectors and eigenvalues, diagonalization of a matrix, symmetric and orthogonal matrices, hermitian and unitary matrices, quadratic forms. (Three 50 minute lectures, one 50 minute recitation)  

21-243 Linear Algebra and Vector Calculus for Engineers  
Fall and Spring: 11 units  
This course will introduce the fundamentals of vector calculus and linear algebra. The topics include vector and matrix operations, determinants, linear systems, matrix eigenvalue problems, vector differential calculus including gradient, divergence, curl, and vector integral calculus including line, surface, and volume integral theorems. Lecture and assignments will emphasize the applications of these topics to engineering problems. (Three 50 minute lectures, one 50 minute recitation)  
Prerequisite: 21-122  

21-256 Multivariate Analysis  
Fall and Spring: 9 units  
This course is designed for students in Economics or Business Administration. Matrix algebra: vectors, matrices, systems of equations, dot product, cross product, lines and planes. Optimization: partial derivatives, the chain rule, gradient, unconstrained optimization, constrained optimization (Lagrange multipliers and the Kuhn-Tucker Theorem). Improper integrals. Multiple integration: iterated integrals, probability applications, triple integrals, change of variables. (Three 50 minute lectures, one 50 minute recitation)  
Prerequisites: 21-120 or 21-112
21-257 Models and Methods for Optimization
Intermittent: 9 units
Introduces basic methods of operations research and is intended primarily for Business Administration and Economics majors. Review of linear systems; linear programming, including the simplex algorithm, duality, and sensitivity analysis; the transportation problem; the critical path method; the knapsack problem, traveling salesman problem, and an introduction to set covering models. (Three 50 minute lectures, one 50 minute recitation) Prerequisites: 21-240 or 21-256 or 21-242 or 21-241 or 18-202 or 06-262

21-259 Calculus in Three Dimensions
All Semesters: 9 units
Vectors, lines, planes, quadratic surfaces, polar, cylindrical and spherical coordinates, partial derivatives, directional derivatives, gradient, divergence, curl, chain rule, maximum-minimum problems, multiple integrals, parametric surfaces and curves, line integrals, surface integrals, Green-Gauss theorems. (Three 50 minute lectures, one 50 minute recitation) Prerequisite: 21-122

21-260 Differential Equations
All Semesters: 9 units
Ordinary differential equations: first and second order equations, applications, Laplace transforms; partial differential equations: partial derivatives, separation of variables, Fourier series; systems of ordinary differential equations; applications. 21-259 or 21-268 or 21-269 are recommended. (Three 50 minute lectures, one 50 minute recitation) Prerequisite: 21-122

21-261 Introduction to Ordinary Differential Equations
Spring: 10 units
A first course in ordinary differential equations intended primarily for math majors and for those students interested in a more conceptual treatment of the subject. One of the goals of this course is to prepare students for upper level courses on differential equations, mathematical analysis and applied mathematics. Students will be required to write rigorous arguments. Topics to be covered: Ordinary differential equations: first and second order equations, applications, Laplace transform, systems of linear ordinary differential equations; systems of nonlinear ordinary differential equations, equilibria and stability, applications. Note: courses 21-259, or 21-268, or 21-269 are recommended. 21-128 or 15-151 can replace 21-127 as a corequisite. (Three 50 minute lectures, one 50 minute recitation) Prerequisite: 21-122

21-268 Multidimensional Calculus
Fall and Spring: 10 units
A serious introduction to multidimensional calculus that makes use of matrices and linear transformation. Results will be stated carefully and rigorously. Students will be expected to write some proofs; however, some of the deeper results will be presented without proofs. Topics to be covered include: functions of several variables, regions and domains, limits and continuity, partial derivatives, linearization and Jacobian matrices, chain rules, inverse and implicit functions, geometric applications, higher derivatives, Taylor's theorem, optimization, vector fields, multiple integrals and change of variables, Leibnitz's rule, line integrals, Green's theorem, parametrization and connectedness, conservative vector fields, surfaces and orientability, surface integrals, divergence theorem and Stokes's theorem. (Three 50 minute lectures, one 50 minute recitation) Prerequisites: 21-122 and (21-242 or 21-241)

21-269 Vector Analysis
Spring: 10 units
A component of the honors program, 21-269 is a more demanding version of 21-268 of greater scope, with greater emphasis placed on rigorous proofs. Topics to be covered typically include: the real field, sups, infs, and completeness; geometry and topology of Euclidean space; limits, continuity, and derivatives of maps between Euclidean spaces; partial derivatives, directional derivatives, gradients, and linearization; inverse and implicit function theorems, geometric applications; higher derivatives, Taylor's theorem, extremal calculus, and Lagrange multipliers; Riemannian integration in Euclidean space, change of variables, iterated integrals and fundamental theorems of one-dimensional calculus; integration of parameterized manifolds, arclength, surface area, and generalizations; conservative and solenoidal vector fields, divergence and curl, Gauss-Green theorems and Stokes's theorem. (Three 50 minute lectures, one 50 minute recitation) Prerequisites: 21-241 Min. grade A or 21-242 Min. grade B

21-270 Introduction to Mathematical Finance
Spring: 9 units
This is a first course for those considering majoring or minoring in Computational Finance. The theme of this course is pricing derivative securities by replication. The simplest case of this idea, static hedging, is used to discuss net present value of a non-random cash flow, internal rate of return, and put-call option parity. Pricing by replication is then considered in a one-period random model. Risk-neutral probability measures, the Fundamental Theorems of Asset Pricing, and an introduction to expected utility maximization and mean-variance analysis are presented in this model. Finally, replication is studied in a multi-period binomial model. Within this model, the replicating strategies for European and American options are determined. (Three 50 minute lectures) Prerequisites: 21-120 or 21-112

21-272 Introduction to Partial Differential Equations
Spring: 9 units
A Partial Differential Equation (PDE for short) is a differential equation involving derivatives with respect to more than one variable. These arise in numerous applications from various disciplines. A prototypical example is the heat equation, governing the evolution of temperature in a conductor. This course will serve as a first introduction to PDE's, and will focus on the most important model equations. It will cover both analytical methods (e.g. separation of variables, Green's functions), numerical methods (e.g. finite elements) and the use of a computer to approximate and visualize solutions. Time permitting, it will touch upon the mathematical ideas behind phenomena observed in nature (e.g. speed of wave propagation, and/or shocks in traffic flow). Prerequisites: (21-268 or 21-259 or 21-269) and (21-261 or 21-260 or 33-231)

21-292 Operations Research I
Spring: 9 units
Operations research offers a scientific approach to decision making, most commonly involving the allocation of scarce resources. This course develops some of the fundamental methods used. Linear programming: the simplex method and its linear algebra foundations, duality, post-optimality and sensitivity analysis; the transportation problem; the critical path method; non-linear programming methods. (Three 50 minute lectures, one 50 minute recitation) Prerequisites: 21-122 and (21-240 or 21-241 or 21-242) and (15-251 or 21-228)

21-295 Putnam Seminar
Fall: 3 units
A problem solving seminar designed to prepare students to participate in the annual William Lowell Putnam Mathematical Competition. Students solve and present their solutions to problems posed. (One 50 minute session)

21-296 Millennium Problems Seminar
Intermittent: 3 units
This seminar course will discuss some of the most important unsolved problems of mathematics (as deemed in 2000 by an international committee of mathematicians): The Riemann Hypothesis; Yang-Mills Theory and the Mass Gap Hypothesis; the P. vs. NP Problem; smoothness of solutions of the Navier-Stokes Equations; the Hodge Conjecture; the Birch and Swinnerton-Dyer Conjecture. If the time allows, the Poincare conjecture will also be discussed. 1 hr. lec.

21-300 Basic Logic
Fall: 9 units
Propositional and predicate logic: Syntax, proof theory and semantics up to completeness theorem, Lowenheim Skolem theorems, and applications of the compactness theorem. (Three 50 minute lectures) Prerequisites: 21-373 or 15-251 or 21-228

21-301 Combinatorics
Fall and Spring: 9 units
A major part of the course concentrates on algebraic methods, which are relevant in the study of error correcting codes, and other areas. Topics covered in depth include permutations and combinations, generating functions, recurrence relations, the principle of inclusion and exclusion, and the Fibonacci sequence and the harmonic series. Additional topics may include existence proofs, partitions, finite calculus, generating combinatorial objects, Polya theory, codes, probabilistic methods. (Three 50 minute lectures) Prerequisites: 21-122 and (21-228 or 15-251)
21-302 Lambda Calculus
Intermittent: 9 units
An introductory course in classical lambda calculus, with an emphasis on syntax. The course will describe many research problems which are suitable topics for senior theses or master’s theses. Topics will include: Basic properties of reduction and conversion; Reduction and conversion strategies; Calculability and representation of data types; Elementary theory of Ershov numberings; Böhm’s theorem, easy terms, and other exotic combinations; Solvability of functional equations (unification); Combinatorics and bases; Simple and algebraic types; Labelled reduction and intersection types; Extensionality and the omega rule. Prerequisites: 80-310 or 21-300 or 15-150

21-320 Symbolic Programming Methods
Intermittent: 9 units
The objective of this course is to learn to program in Maple, a powerful symbolic mathematics package available on many platforms at Carnegie Mellon. After learning what Maple can do with the commands provided with the package, students will learn to develop their own Maple functions to accomplish extended mathematical computations. Grades in the course will be based mostly on project work. Projects may come from any relevant field and may be graphical, numerical, or symbolic or all three. The course will involve online demonstrations in most classes. 3 hrs. lec. Prerequisites: (21-127 or 15-151 or 21-128) and 21-122

21-325 Probability
Fall and Spring: 9 units
This course focuses on the understanding of basic concepts in probability theory and illustrates how these concepts can be applied to develop and analyze a variety of models arising in computational biology, finance, engineering and computer science. The firm grounding in the fundamentals is aimed at providing students the flexibility to build and analyze models from diverse applications as well as preparing the interested student for advanced work in these areas. The course will cover core concepts such as probability spaces, random variables, random vectors, multivariate densities, distributions, expectations, sampling and simulation; independence, conditioning, conditional distributions and expectations; limit theorems such as the strong law of large numbers and the central limit theorem; as well as additional topics such as large deviations, random walks and Markov chains, as time permits. (Three 50 minute lectures) Prerequisites: 21-259 or 21-268 or 21-269

21-329 Set Theory
Spring: 9 units
Set theory was invented about 110 years ago by George Cantor as an instrument to understand infinite objects and to compare different sizes of infinite sets. Since then set theory has come to play an important role in many branches of modern mathematics, and serves as a foundation of mathematics. Contents: Basic properties of natural numbers, countable and uncountable sets, construction of the real numbers, some basic facts about cardinal numbers and cardinal arithmetic, the continuum hypothesis, well ordered sets, ordinal numbers and transfinite induction, the axiom of choice, Zorn’s lemma. Optional topics if time permits: infinitary combinatorics, filters and large cardinals, Borel and analytic sets of reals. (Three 50 minute lectures) Prerequisites: 21-127 or 15-151 or 21-128

21-341 Linear Algebra
Fall and Spring: 9 units
21-341 Linear Algebra. A mathematically rigorous treatment of linear algebra over an arbitrary field. Topics studied will include abstract vector spaces, linear transformations, determinants, eigenvalues, eigenvectors, inner products, invariant subspaces, canonical forms, the spectral theorem and the singular value decomposition. 21-373 recommended. (Three 50 minute lectures) Prerequisites: 21-373 or 21-241 or 21-242

21-344 Numerical Linear Algebra
Spring: 9 units
An introduction to algorithms pertaining to matrices and large linear systems of equations. Direct methods for large sparse problems including graph data structures, maximum matchings, row and column orderings, and pivoting strategies. Iterative methods including Conjugate Gradient and GMRES, with a discussion of preconditioning strategies. Additional topics include: computation of eigenvalues and eigenvectors, condition numbers, the QR and singular value decompositions, least-squares systems. (Three 50 minute lectures) Prerequisites: 15-112 and (21-242 or 21-241 or 21-240) (and 21-269 or 21-268 or 21-259)

21-355 Principles of Real Analysis I
Fall and Spring: 9 units
This course provides a rigorous and proof-based treatment of functions of one real variable. The Real Number System: Field and order axioms, sups and infs, completeness, integers and rational numbers. Real Sequences: Limits, cluster points, limsup and liminf, subsequences, monotonic sequences, Cauchy’s criterion, Bolzano-Weierstrass Theorem. Topology of the Real Line: Open sets, closed sets, density, compactness, Heine-Borel Theorem. Continuity: attainment of extrema, Intermediate Value Theorem, uniform continuity. Differentiation: Chain Rule, local extrema, Mean-Value Theorems, L'Hospital's Rule, Taylor's Theorem. Riemann Integration: Partitions, upper and lower integrals, sufficient conditions for integrability, Fundamental Theorem of Calculus, Sequences of Functions: Pointwise convergence, uniform convergence, interchanging the order of limits. The course presumes some mathematical sophistication including the ability to recognize, read, and write proofs. (Three 50 minute lectures) Prerequisites: (15-151 or 21-128 or 21-127) and 21-122

21-356 Principles of Real Analysis II
Fall and Spring: 9 units
This course provides a rigorous and proof-based treatment of functions of several real variables. Topology in metric spaces, specialization to finite dimensional normed linear spaces. Vector differential calculus: continuity and the total derivative, partial derivatives, directional derivatives, gradients, Jacobians, the chain rule, implicit function theorem. Vector integral calculus: double and triple integrals, arclength and surface area, line integrals, Green’s Theorem, surface integrals, Divergence and Stokes Theorems. If time permits: trigonometric series, Fourier series for orthonormal bases, minimization of square error. The course presumes some mathematical sophistication including the ability to recognize, read, and write proofs. 21-268 or 21-269 are strongly recommended rather than 21-259. (Three 50 minute lectures) Prerequisites: (21-269 or 21-268 or 21-259) and 21-241 and 21-355

21-360 Differential Geometry of Curves and Surfaces
Intermittent: 9 units
The course is a rigorous introduction to the differential and integral calculus of curves and surfaces. Topics to be covered include: Parameterized and regular curves Frenet equations canonical coordinate system, local canonical forms, global properties of plane curves Regular surfaces, differential functions on surfaces, the tangent plane and differential of a map, orientation of surfaces, characterization of compact orientable surfaces, classification of compact surfaces The geometry of the Gauss map, isometries and conformal maps, parallel transport, geodesics, the Gauss-Bonnet theorem and applications. More topics may be covered, as time allows. Students should be prepared to write proofs and perform computations. 21-356 and 21-236 are recommended. (Three 50 minute lectures) Prerequisites: 21-268 or 21-269

21-366 Topics in Applied Mathematics
Intermittent: 9 units
Typical of courses that might be offered from time to time are game theory, non-linear optimization, and dynamic programming. Prerequisites will depend on the content of the course. (Three 50 minute lectures)

21-369 Numerical Methods
Fall and Spring: 12 units
This course provides an introduction to the use of computers to solve scientific problems. Methods for the computational solution of linear algebra systems, nonlinear equations, the interpolation and approximation of functions, differentiation and integration, and ordinary differential equations. Analysis of roundoff and discretization errors and programming techniques. 21-268 or 21-269 are recommended rather than 21-259. (Three 50 minute lectures, one 50 minute recitation) Prerequisites: (15-112 or 15-110) and (21-268 or 21-259 or 21-269) and (21-240 or 21-242 or 21-241) (and 21-260 or 21-261 or 21-630 or 33-231)

21-370 Discrete Time Finance
Fall: 9 units
This course introduces the Black-Scholes option pricing formula, shows how the binomial model provides a discretization of this formula, and uses this connection to fit the binomial model to data. It then sets the stage for Continuous-Time Finance by discussing in the binomial model the mathematical technology of filtrations, martingales, Markov processes and risk-neutral measures. Additional topics are American options, expected utility maximization, the Fundamental Theorems of Asset Pricing in a multi-period setting, and term structure modeling, including the Heath-Jarrow-Morton model. Students in 21-370 are expected to read and write proofs. Acceptable co-requisites include 21-325, 15-259 or 36-218 (Three 50 minute lectures) Prerequisites: (21-270 or 70-492) and (21-268 or 21-269 or 21-256 or 21-259)
21-371 Functions of a Complex Variable
Fall: 9 units
This course provides an introduction to one of the basic topics of both pure and applied mathematics and is suitable for those with both practical and theoretical interests. Algebra and geometry of complex numbers; complex differentiation and integration. Cauchy's theorem and applications; conformal mapping; applications. 21-268 or 21-269 are recommended prerequisites, rather than 21-259. (Three 50 minute lectures)
Prerequisites: 21-355 or 21-235

21-373 Algebraic Structures
Fall and Spring: 9 units
Prerequisites: (15-151 or 21-127 or 21-128) and (21-241 or 21-242)

21-374 Field Theory
Spring: 9 units
The purpose of this course is to provide a successor to Algebraic Structures, with an emphasis on applications of groups and rings within algebra to some major classical problems. These include constructions with a ruler and compass, and the solvability or unsolvability of equations by radicals. It also offers an opportunity to see group theory and basic ring theory "in action", and introduces several powerful number theoretic techniques. The basic ideas and methods required to study finite fields will also be introduced. These ideas have recently been applied in a number of areas of theoretical computer science including primality testing and cryptography. (Three 50 minute lectures)
Prerequisite: 21-373

21-375 Topics in Algebra
Intermittent: 9 units
Typical of courses that might be offered from time to time are elliptic curves, commutative algebra, and theory of Boolean functions. (Three 50 minute lectures)
Prerequisite: 21-373

21-377 Monte Carlo Simulation for Finance
Intermittent: 9 units
First course in Monte Carlo simulation, with applications to Mathematical Finance. Students will put into practice many of the theoretical ideas introduced in Continuous Time Finance. Topics to be covered: random variable/stochastic process generation; options pricing; variance reduction; Markov chain Monte Carlo Methods.
Prerequisites: 21-325 Min. grade B or 21-420

21-378 Mathematics of Fixed Income Markets
Fall: 9 units
A first course in fixed income. Students will be introduced to the most common securities traded in fixed income markets and the valuation methods used to price them. Topics covered include discount factors; interest rates basics; pricing of coupon bonds; identifying the yield to maturity, as well as bond sensitivities to interest rates; term structure modeling; forward and swap rates; fixed income derivatives (including mortgage backed securities) and their valuation through backwards induction; fixed income indexes and return attribution. For a co-requisite, 36-225 can be accepted as an alternative for 21-325. (Three 50 minute lectures)
Prerequisite: 21-270 Min. grade B

21-380 Introduction to Mathematical Modeling
Intermittent: 9 units
This course shall examine mathematical models, which may be used to describe natural phenomena. Examples, which have been studied include: continuum description of highway traffic, ocean velocity models of a monotonic gas, chemotactic behavior in biological systems, European and American options pricing, and cellular-automata. Systems such as the first four are described by partial differential equations; the last involves discrete-time and discrete-space dynamical systems, which have been used to successfully represent both physical and biological systems. The course will develop these models and then examine the behavior of the underlying systems, both analytically and numerically. The mathematical tools required will be developed in the course. (Three 50 minute lectures)
Prerequisites: (21-241 or 21-242) and (21-260 or 21-261)

21-393 Operations Research II
Fall: 9 units
Building on an understanding of Linear Programming developed in 21-292 Operations Research I, this course introduces more advanced topics. Integer programming, including cutting planes and branch and bound. Dynamic programming. An introduction to Combinatorial Optimization including optimal spanning trees, shortest paths, the assignment problem and max-flow/min-cut. The traveling salesman problem and NP-completeness. An important goal of this course is for the student to gain experience with the process of working in a group to apply operations research methods to solve a problem. A portion of the course is devoted to a group project based upon case studies and the methods presented. 36-410 recommended. (Three 50 minute lectures)
Prerequisites: (15-251 or 21-228) and 21-292

21-400 Intermediate Logic
Intermittent: 9 units
This course builds on the proof theory and model theory of first-order logic covered in 21-300. These are applied in 21-400 to Peano Arithmetic and its standard model, the natural numbers. The main results are the incompleteness, undefinability and undecidability theorems of Godel, Tarski, Church and others. Leading up to these, it is explained how logic is formalized within arithmetic, how this leads to the phenomenon of self-reference, and what it means for the axioms of a theory to be computably enumerable. Related aspects of computability theory are included to the extent that time permits.
Prerequisite: 21-300

21-410 Research Topics in Mathematical Sciences
All Semesters: 9 units
This course affords undergraduates to pursue elementary research topics in the area of expertise of the instructor. The prerequisites will depend on the content of the course. (Three 50 minute lectures)

21-420 Continuous-Time Finance
Spring: 9 units
This course begins with Brownian motion, stochastic integration, and Ito's formula from stochastic calculus. This theory is used to develop the Black-Scholes option pricing formula and the Black-Scholes partial differential equation. Additional topics may include models of credit risk, simulation, and expected utility maximization. (Three 50 minute lectures)
Prerequisites: (18-202 or 21-260) and 21-370 and (36-217 or 21-325 or 36-218 or 15-259)

21-435 Applied Harmonic Analysis
Intermittent: 9 units
This course serves as a broad introduction to harmonic analysis and its applications, particularly in 1-dimensional signal processing, for undergraduate students in mathematics, engineering, and the applied sciences. Topics include: Discrete Fourier transform and fast Fourier transform; Fourier series and the Fourier transform; Hilbert spaces and applications; Shannon sampling theorem, bandlimited functions, uncertainty principle; Wavelets and multi-resolution analysis; Applications in image processing. (Three 50 minute lectures)
Prerequisites: (21-355 or 21-235) and (21-241 or 21-242)

21-441 Number Theory
Fall: 9 units
Number theory deals with the integers, the most basic structures of mathematics. It is one of the most ancient, beautiful, and well-studied branches of mathematics, and has recently found surprising new applications in communications and cryptography. Course contents: Structure of the integers, greatest common divisors, prime factorization. Modular arithmetic, Fermat's Theorem, Chinese Remainder Theorem. Number theoretic functions, e.g. Euler's function, Mobius functions, and identities. Diophantine equations, Pell's Equation, continued fractions. Modular polynomial equations, quadratic reciprocity. (Three 50 minute lectures)
Prerequisites: (21-242 or 21-241) and 21-373

21-465 Topology
Intermittent: 9 units
Prerequisites: 21-355 and 21-373
21-467 Differential Geometry
Intermittent: 9 units
This course will provide a thorough and rigorous introduction to differential geometry on manifolds. Contents: Differentiable manifolds; tangent spaces; vector fields and n-forms; integral curves; cotangent vectors; tensors on Riemannian metrics; connection; parallel transport; geodesics and convex neighborhoods; sectional, Ricci, scalar curvatures; tensors on Riemannian manifolds; Lie groups; transformation groups.
Prerequisites: 21-356 and 21-373

21-469 Computational Introduction to Partial Differential Equations
Intermittent: 12 units
A Partial Differential Equation (PDE for short) is a differential equation involving derivatives with respect to more than one variable. These arise in numerous applications from various disciplines. Most PDEs do not have explicit solutions, and hence computational methods are essential for understanding the underlying phenomena. This course will serve as a first introduction to PDEs and their numerical approximation, and will focus on a variety of mathematical models. It will cover both analytical methods, numerical methods (e.g. finite differences) and the use of a computer to approximate and visualize solutions. The mathematical ideas behind phenomena observed in nature will be studied at the theoretical level and in numerical simulations (e.g. speed of wave propagation, and/or shocks in traffic flow). Topics will include: Derivation of PDEs from physical principles, analytical and computational tools for the transport equation and the Poisson equation, Fourier analysis, analytical and numerical techniques for the solution of parabolic equations and if time permits, the wave equation.
(Three 50 minute lectures, one 80 minute recitation)
Prerequisites: (21-241 or 21-240 or 21-242) and (21-259 or 21-268 or 21-269) and (21-261 or 21-630 or 33-231 or 21-260) and (15-110 or 15-112)

21-470 Selected Topics in Analysis
Intermittent: 9 units
Typical of courses, which are offered from time to time are finite difference equations, calculus of variations, and applied control theory. The prerequisites will depend on the content of the course. 3 hrs. lec.
Prerequisites: 21-241 and 21-260 and 21-259

21-476 Introduction to Dynamical Systems
Intermittent: 9 units
This course is an introduction to differentiable dynamical systems. The material includes basic properties of dynamical systems, including the existence and uniqueness theory, continuation, singular points, orbits, and their classification. The Poincare’-Bendixon theorem and typical applications, like Lienard equations and Lotka-Volterra are also covered. An introduction to chaos as time permits. 3 hrs. lec.
Prerequisites: (21-242 or 21-241) and 21-261

21-484 Graph Theory
Spring: 9 units
Graph theory uses basic concepts to approach a diversity of problems and nontrivial applications in operations research, computer science and other disciplines. It is one of the very few mathematical areas where one is always close to interesting unsolved problems. Topics include graphs and subgraphs, trees, connectivity, Euler tours and Hamilton cycles, matchings, graph coloring, planar graphs and Euler’s Formula, directed graphs, network flows, counting arguments, and graph algorithms. (Three 50 minute lectures)
Prerequisites: (21-228 or 15-251) and (21-241 or 21-242)

21-499 Undergraduate Research Topic
Intermittent: 9 units
This course affords undergraduates to pursue elementary research topics in the area of expertise of the instructor. The prerequisites will depend on the content of the course.

21-590 Practicum
All Semesters: 3 units
Students in this course gain experience with the application of mathematical models to business and/or industrial problems during an internship. The internship is set up by the student in consultation with a faculty mentor. The students must indicate a mentor at the internship, who together with the faculty member develops a description of the goals of the internship. The internship must include the opportunity to learn about problems which have mathematical content.

21-599 Undergraduate Reading and Research
Fall and Spring
Individual reading courses or projects in mathematics and its applications. Prerequisites and units to be negotiated with individual instructors.

21-602 Introduction to Set Theory I
Fall: 12 units
The axioms of ZFC, ordinal arithmetic, cardinal arithmetic including Konig's lemma, class length induction and recursion, the rank hierarchy, the Mostowski collapse theorem, the Hierarchy, the Delta_1 absoluteness theorem, the absoluteness of wellfoundedness, the reflection theorem for hierarchies of sets, ordinal definability, the model HOD, relative consistency, Goedel's theorem that HOD is a model of ZFC, constructibility, Goedel's theorem that L is a model of ZFC + GCH, the Borel and Projective hierarchies and their effective versions, Suslin representations for Sigma^1_1, Pi^1_1 and Sigma^1_2, sets of reals, Shoenfield's absoluteness theorem, the complexity of sets of constructible reals, the combinatorics of club and stationary sets (including the diagonal intersection, the normality of the club filter, Fodor's lemma and its applications), Solovay's splitting theorem, model theoretic techniques commonly applied in set theory (e.g., elementary substructures, chains of models and ultrapowers), club and stationary subsets of [X]^omega and their combinatorics, Jensen's diamond principles and his proofs that they hold in L, Gregory's theorem and generalizations, constructions of various kinds of uncountable trees (including Aronszajn, special, Suslin, Kripke, Jensen's square principles and elementary applications, the basic theory of large cardinals (including inaccessible, Mahlo, weakly compact and measurable cardinals), Scott's theorem that there are no measurable cardinals in L, Kunen's theorem that the only elementary embedding from V to V is the identity. Optional topic: SCH and Silver's theorem. (Three 50 minute lectures)
Prerequisites: (21-355 Min. grade B or 21-235 Min. grade B) and (21-373 Min. grade B or 21-237 Min. grade B)

21-603 Model Theory I
Intermittent: 12 units
Similarity types, structures; downward Lowenheim Skolem theorem; construction of models from constants, Henkin's omitting types theorem, prime models; elementary chains of models, basic two cardinal theorems, saturated models, basic results on countable models including Ryll-Nardzewski theorem; indiscernible sequences, Ehrenfeucht-Mostowski models; introduction to stability, rank functions, primary models, and a proof of Morley's catagoricity theorem; basic facts about infinitary languages, computation of Hanf-Morley numbers. (Three 50 minute lectures)
Prerequisites: 21-355 Min. grade B and 21-373 Min. grade B

21-604 Introduction to Recursion Theory
Intermittent: 12 units
Models of computation, computable functions, solvable and unsolvable problems, reducibilities among problems, recursive and recursively enumerable sets, the recursion theorem, Post's problem and the Friedberg-Muchnik theorem, general degrees and r.e. degrees, the arithmetic hierarchy, the hyper-arithmetic hierarchy, the analytical hierarchy, higher type recursion. (Three 50 minute lectures)
Prerequisites: 21-355 Min. grade B and 21-373 Min. grade B

21-610 Algebra I
Intermittent: 12 units
The structure of finitely generated abelian groups, the Sylow theorems, nilpotent and solvable groups, simplicity of alternating and projective special linear groups, free groups, the Nielsen-Schreier theorem. Vector spaces over division rings, field extensions, the fundamental Galois correspondence, algebraic closure. The Jacobson radical and the structure of semisimple rings. Time permitting, one of the following topics will be included: Wedderburn's theorem on finite division rings, Frobenius' Theorem. Prerequisite: Familiarity with the content of an undergraduate course on groups and rings. (Three 50 minute lectures)
Prerequisites: 21-355 Min. grade B and 21-373 Min. grade B

21-620 Real Analysis
Fall: 6 units
A review of one-dimensional, undergraduate analysis, including a rigorous treatment of the following topics in the context of real numbers: sequences, compactness, continuity, differentiation, Riemann integration. (Mini-course. Normally taken with 21-621.) (Three 50 minute lectures)
Prerequisites: (21-128 Min. grade B or 21-127 Min. grade B or 15-151 Min. grade B) and 21-122 Min. grade B

21-621 Introduction to Lebesgue Integration
Fall: 6 units
Construction of Lebesgue measure and the Lebesgue integral on the real line. Fatou's Lemma, the monotone convergence theorem, the dominated convergence theorem. (Mini-course. Normally taken with 21-620.) (Three 50 minute lectures)
Prerequisite: 21-620 Min. grade B
21-623 Complex Analysis
Intermittent: 12 units
The complex plane, holomorphic functions, power series, complex integration, and Cauchy’s Theorem. Calculus of residues. Additional topics may include conformal mappings and the application of complex transforms to differential equations. (Three 50 minute lectures)
Prerequisites: 21-373 Min. grade B and 21-355 Min. grade B

21-624 Selected Topics
Intermittent: 12 units
Content varies. May be taken more than once if content is sufficiently different.
Prerequisites: 21-329 Min. grade B or 21-602 Min. grade B

21-630 Ordinary Differential Equations
Intermittent: 12 units
Basic concepts covered are existence and uniqueness of solutions, continuation of solutions, continuous dependence, and stability. For autonomous systems, topics included are: orbits, limit sets, Liapunov’s direct method, and Poincaré-Bendixson theory. For linear systems, topics included are: fundamental solutions, variation of constants, stability, matrix exponential solutions, and saddle points. Time permitting, one or more of the following topics will be covered: differential inequalities, boundary-value problems and Sturm-Liouville theory, Floquet theory. (Three 50 minute lectures)
Prerequisites: 21-373 Min. grade B and 21-355 Min. grade B

21-632 Introduction to Differential Equations
Fall: 12 units
This course serves as a broad introduction to Ordinary and Partial Differential Equations for beginning graduate students and advanced undergraduate students in mathematics, engineering, and the applied sciences. Mathematical sophistication in real analysis at the level of 21-355/356 is assumed. Topics include: essentials of Ordinary Differential Equations, origins of Partial Differential Equations, the study of model problems including the Poisson and Laplace equations, the heat equation, the transport equation, and the wave equation. (Three 50 minute lectures)
Prerequisites: 21-373 Min. grade B and 21-355 Min. grade B

21-640 Introduction to Functional Analysis
Spring: 12 units
Prerequisites: 21-355 Min. grade B and 21-373 Min. grade B

21-651 General Topology
Fall: 12 units
Prerequisites: 21-355 Min. grade B and 21-373 Min. grade B

21-660 Introduction to Numerical Analysis I
Spring: 12 units
Finite precision arithmetic, interpolation, spline approximation, numerical integration, numerical solution of linear and nonlinear systems of equations, optimization in finite dimensional spaces. (Three 50 minute lectures)
Prerequisites: 21-355 Min. grade B and 21-373 Min. grade B

21-670 Linear Algebra for Data Science
Fall: 6 units
This course is designed to present and discuss those aspects of Linear Algebra that are most important in Data Analytics. The emphasis will be on developing intuition and understanding how to use linear algebra, rather than on proofs. (Three 50 minute lectures)
Prerequisites: 21-355 Min. grade B and 21-373 Min. grade B

21-671 Computational Linear Algebra
Fall: 12 units
This is a survey of methods in computational linear algebra. Topics covered in this course focus around algorithms for solving (dense or sparse) linear systems. Regularization and underdetermined systems will be discussed in detail. Rather than assuming prior knowledge in numerical analysis or matrix theory, we will introduce standard methods or results when needed. In this way, much of the material is self-contained. Theoretical and experimental results will be covered accordingly, with an emphasis on cost, stability, and convergence. (Three 50 minute lectures)
Prerequisites: (21-240 or 21-241 or 21-242) and (21-269 or 21-268 or 21-259)

21-681 Stochastic Calculus in Finance
All Semesters: 6 units
This is a graduate-level introduction to continuous-time equilibrium asset pricing models. Using tools from Itô calculus, the first part of the course covers the benchmark case of complete, frictionless markets, for which a fairly general theory and a number of solvable examples have been developed. The second part of the course then provides an overview of the cutting-edge research on extensions of the baseline model that account for “flaws and frictions” such as heterogeneous beliefs, trading costs, or asymmetric information. In the third part of the course, students will present a related research paper, chosen together with the instructor in accordance with their background and research interests. (One 80 minute lecture)
Prerequisites: 21-355 Min. grade B and 21-373 Min. grade B

21-690 Methods of Optimization
Fall: 12 units
Prerequisites: 21-355 Min. grade B and 21-373 Min. grade B

21-701 Discrete Mathematics
Fall: 12 units
Combinatorial analysis, graph theory with applications to problems in computational complexity, networks, and other areas. (Three 50 minute lectures)
Prerequisites: 21-373 Min. grade B and 21-355 Min. grade B

21-702 Set Theory II
Spring: 12 units
This course is a sequel to 21-602 Set Theory. The main goal is to prove Solovay’s theorem that Con(ZFC + an inaccessible cardinal) implies Con(ZF + DC + every set of reals is Lebesgue measurable). Topics covered include absoluteness theorems, Borel codes, the Levy collapse, product forcing, relative constructibility, and the basics of iterated forcing up to the consistency of Martin’s Axiom. (Three 50 minute lectures)
Prerequisites: 21-602 Min. grade B

21-703 Model Theory II
All Semesters: 12 units
The course concentrates in what is considered “mainstream model theory” with is Shelah’s classification theory (known also as Stability). Among the topics to be presented are stability, superstability, the theory of various notions of primeness, rank functions, forking calculus, the stability spectrum theorem, finite equivalence relations theorem, stable groups (up to and including the Macintyre-Cherlin-Shelah theorem on super-stable fields), and some elementary geometric model theory. If time permits also: basic facts about infinitary languages, computation of Hanf-Morley numbers; some of the Ax-Kochen-Ershov theory of model theory for fields with valuations (will apply this to solve Artin’s conjecture). (Three 50 minute lectures)
Prerequisites: 21-603 Min. grade B

Course Website: http://www.math.cmu.edu/~rami/mt2.11.desc.html
21-720 Measure and Integration
Fall: 12 units
The Lebesgue integral, absolute continuity, signed measures and the Radon-Nikodym Theorem, Lp spaces and the Riesz Representation Theorem, product measures and Fubini's Theorem. (Three 50 minute lectures)
Prerequisites: 21-355 Min. grade B and 21-373 Min. grade B

21-721 Probability
Spring: 12 units
Probability spaces, random variables, expectation, independence, Borel-Cantelli lemmas, Kernels and product spaces, existence of probability measures on infinite product spaces, Kolmogorov's zero-one law. Weak and strong laws of large numbers, ergodic theorems, stationary sequences. Conditional expectation: characterization, construction and properties. Relation to kernels, conditional distribution, density, filtration, adapted and predictable processes, martingales, stopping times, upcrossing inequality and martingale convergence theorems, backward martingales, optional stopping, maximal inequalities. Various applications of martingales: branching processes, Polya's urn, generalized Borel-Cantelli, Levy's 0-1 law, martingale method, strong law of large numbers, etc. Weak convergence of probability measures, characteristic functions of random variables, weak convergence in terms of characteristic functions. Central limit theorem, Poisson convergence, Poisson process, Large deviations, rate functions, Cramer's Theorem. (Three 50 minute lectures)
Prerequisite: 21-720 Min. grade B

21-723 Advanced Real Analysis
Spring: 12 units
This course is a sequel to 21-720 (Measure and Integration). It is meant to introduce students to a number of important advanced topics in analysis. Topics include: distributions, Fourier series and transform, Sobolev spaces, Bochner integration, basics of interpolation theory, integral transforms. (Three 50 minute lectures)
Prerequisite: 21-720 Min. grade B

21-732 Partial Differential Equations I
Fall: 12 units
An introduction to the modern theory of partial differential equations. Including functional analytic techniques. Topics vary slightly from year to year, but generally include existence, uniqueness and regularity for linear elliptic boundary value problems and an introduction to the theory of evolution equations. (Three 50 minute lectures)
Prerequisites: 21-373 Min. grade B and 21-355 Min. grade B

21-737 Probabilistic Combinatorics
Intermittent: 12 units
This course covers the probabilistic method for combinatorics in detail and introduces randomized algorithms and the theory of random graphs. Methods covered include the second moment method, the Rödl nibble, the Lovász local lemma, correlation inequalities, martingale's and tight concentration, Janson's inequality, branching processes, coupling and the differential equations method for discrete random processes. Objects studied include the configuration model for random regular graphs, Markov chains, the phase transition in the Erdős-Rényi random graph, and the Barabási-Albert preferential attachment model. (Three 50 minute lectures)
Prerequisites: 21-301 and (15-259 or 36-218 or 36-225 or 21-325)

21-738 Extremal Combinatorics
Intermittent: 12 units
Classical problems and results in extremal combinatorics including the Turán and Zarankiewicz problems, the Erdős and #337;s-Stone theorem and the Erdős-Simonovits stability theorem. Extremal set theory including the Erdős and #337;s-Rado sunflower lemma and variations, VC-dimension, and Kneser's conjecture. The Szemerédi regularity lemma. Algebraic methods including finite field constructions and eigenvalues and expansion properties of graphs. Shannon capacity of graphs. Chromatic number of Rn and Borsuk's conjecture. Graph decomposition including Graham-Pollack and Baranyai's theorem. (Three 50 minute lectures)
Prerequisites: 21-373 Min. grade B and 21-355 Min. grade B

21-742 Calculus Of Variations
Intermittent: 12 units
Classical fixed endpoint examples. Fixed endpoint problems in classes of absolutely continuous functions: existence via lower semicontinuity. Tonelli's existence theorem. Euler-Lagrange and DuBois Reymond equations, transversality conditions, Weierstrass field theory, Hamilton-Jacobi theory. Problems with constraints. (Three 50 minute lectures)
Prerequisites: 21-355 Min. grade B and 21-373 Min. grade B

21-752 Algebraic Topology
Fall and Spring: 12 units
Topology is a less rigid variant of geometry that studies shapes of spaces. Algebraic topology associates algebraic invariants, such as groups or rings, to such spaces. This is achieved by building a space from simpler ones or by algebraically keeping track of how to map a simple space into a given space. This course will cover the fundamental group and covering spaces, homology theories, and the cohomology ring of a space (time permitting). (Three 50 minute lectures)
Prerequisite: 21-651 Min. grade B

21-759 Differential Geometry
Intermittent: 12 units
Manifolds in Euclidean spaces, curves and surfaces, principal curvatures, geodesics. Surfaces with constant mean curvature, minimal surfaces. Abstract differentiable manifolds, tangent spaces, vector bundles, affine connections, parallelisms, covariant gradients, Cartan torsion, Riemann curvature. Riemannian geometry, Lie groups. Familiarity with analysis in finite dimensional spaces will be assumed. (Three 50 minute lectures)
Prerequisites: 21-373 Min. grade B and 21-355 Min. grade B

21-762 Finite Element Methods
Intermittent: 12 units
Prerequisites: 21-355 Min. grade B and 21-373 Min. grade B

21-765 Introduction to Parallel Computing and Scientific Computation
Spring: 9 units
Course objectives: to develop structural intuition of how the hardware and the software work, starting from simple systems to complex shared resource architectures; to provide guidelines about how to write and document a software package; to familiarize the audience with the main parallel programming techniques and the common software packages/libraries. (One 110 minute lecture)
Prerequisites: 21-373 Min. grade B and 21-355 Min. grade B
Course Website: http://www.math.cmu.edu/~florin/M21-765/index.html (http://www.math.cmu.edu/~florin/M21-765/)

21-801 Advanced Topics in Discrete Mathematics
Intermittent: 12 units
Content varies. May be taken more than once if content is sufficiently different. Please contact the instructor or the department for the most recent description. (Three 50 minute lectures)
Prerequisites: 21-373 Min. grade B and 21-355 Min. grade B

21-803 Model Theory III
All Semesters: 12 units
We will concentrate in classification theory for first-order theories. The theory was developed mostly by Saharon Shelah presented in his 1978 (2nd ed 1990) book and in several hundreds of papers. We will present a modern overview of Shelah's theory incorporating few recent innovations and simplifications. The development of the theory was motivated by set-theoretic questions like: "what is the asymptotic behavior of the function (lalpha, al) as a function of al?" and "what is the first lambda such that an uncountable first-order stable theory T is stable in llambda?" Surprisingly the full answer to such combinatorial set-theoretic questions led for a development and discovery of a conceptually rich theory which seems to be related to aspects of commutative algebra and algebraic-geometry. This theory found several applications in the form of solving fundamental problems in classical fields of mathematics among them geometry and number theory. The focus will be on the simplest and most fundamental aspects of the pure theory. Primarily around a notion called forking and various characterizations of classes of theories. (Three 50 minute lectures)
Prerequisites: 21-355 Min. grade B and 21-373 Min. grade B

21-820 Advanced Topics in Analysis
Intermittent: 12 units
Content varies. May be taken more than once if content is sufficiently different. Please contact the instructor or the department for the most recent description. (Three 50 minute lectures)
Prerequisites: 21-373 Min. grade B and 21-355 Min. grade B

21-829 Introduction to Algebraic Topology
Fall: 12 units
The fundamental properties of homotopy and homology of topological spaces. Applications to various characterizations of classes of theories. (Three 50 minute lectures)

21-853 Mathematical Logic III
Intermittent: 12 units
The focus will be on the simplest and most fundamental aspects of the pure theory. Primarily around a notion called forking and various characterizations of classes of theories. (Three 50 minute lectures)
Prerequisites: 21-355 Min. grade B and 21-373 Min. grade B

Course Website: http://www.math.cmu.edu/~florin/M21-765/index.html
21-830 Advanced Topics in Partial Differential Equations
All Semesters: 12 units
The course is on the calculus in infinite dimensional Gaussian space, and its various connections to subjects including harmonic analysis, Stein’s method in normal approximation, stochastic PDE, etc. The prerequisites include basic probability and partial differential equations. (Three 50 minute lectures)
Prerequisites: 21-355 Min. grade B and 21-632

21-832 Partial Differential Equations II
Intermittent: 12 units
Elliptic boundary value problems, Green’s theorem calculations, integral equation methods, variational formulations and Galerkin’s method, regularity theory, parabolic problems and semigroups.
Prerequisites: 21-373 Min. grade B and 21-355 Min. grade B

21-860 Advanced Topics In Numerical Analysis
Intermittent: 12 units
Content varies. May be taken more than once if content is sufficiently different. (Three 50 minute lectures)
Prerequisites: 21-373 Min. grade B and 21-355 Min. grade B

21-880 Stochastic Calculus
All Semesters: 12 units
This is a first Ph.D.-level course in stochastic calculus for continuous-time processes. It includes martingales and semi-martingales, Brownian motion, the Poisson process, representation of continuous martingales as time-changed Brownian motions, construction of the Itô integral, and Itô’s formula. (Two 80 minute lectures)
Prerequisites: 21-373 Min. grade B and 21-355 Min. grade B

21-882 Advanced Topics in Financial Mathematics
Intermittent: 12 units
Content varies. May be taken more than once if content is sufficiently different. (Two 80 minute lectures)
Prerequisites: 21-373 Min. grade B and 21-355 Min. grade B