Mathematics (MATH)

Course information contained within the Bulletin is accurate at the time of publication in June 2025 but is subject to change. For the most up-to-date course information, please refer to the Course Catalog.

MATH 5000. Special Topics in Math. 3 Credit Hours.
Repeatability: This course may be repeated for additional credit.

MATH 5001. Linear Algebra. 3 Credit Hours.
Vector spaces and subspaces over the real and complex numbers; linear independence and bases; linear mappings; dual and quotient spaces; fields and general vector spaces; polynomials, ideals and factorization of polynomials; determinant; Jordan canonical form. Fundamentals of multilinear algebra.

Repeatability: This course may not be repeated for additional credits.

MATH 5003. Professional Development Seminar. 1 Credit Hour.
This class advances intentional Professional Development by creating an online professional profile and portfolio that allows employers to determine the strength of a student's candidacy for a specific job. Students develop an online professional profile, attend a Professional Development Workshop and write a White paper which demonstrates analytical and technical writing skills on a topic of interest to the student. The White Paper proposes a change in any STEM area where a lack of efficiency in a process, or gap in knowledge, in an area of research, exists. Finally, students organize a networking event by inviting speakers, hiring managers and graduate students in CST.

Repeatability: This course may not be repeated for additional credits.

MATH 5005. Ethics in Computing. 2 Credit Hours.
This course will examine the social, legal, and privacy issues applying to scientific data. Students will be given the opportunity to discuss contemporary case studies, in addition to NIH-sanctioned online training modules (Responsible Conduct in Research). The case-study based approach used in class will expose students to ethics of database management and security, open-access and open-source philosophies, the ethics of collecting, storing, and disseminating data.

Repeatability: This course may not be repeated for additional credits.

MATH 5007. Combinatorics. 3 Credit Hours.
Basic theorems and applications of combinatorial analysis, including generating functions, difference equations, Polya's theory of counting, graph theory, matching, and block diagrams.

Repeatability: This course may not be repeated for additional credits.

MATH 5011. Algebra and Functions for Teaching. 3 Credit Hours.
This class will broaden and deepen our understanding of algebra and functions and their many applications. We will begin with an examination of the concept of function generally and then look at examples. We will consider the usefulness of functions, both in modeling real phenomena and in solving equations. We will carefully develop more advanced concepts from basic principles and logic as we proceed from polynomial functions to rational, radical, exponential, logarithmic, and trigonometric functions. As we do this, we will explore non-traditional teaching techniques and tools such as the practice of inquiry-based learning and the appropriate use of technology. We will also utilize and discuss the eight Mathematical Practice Standards set forth in the Common Core State Standards.

Repeatability: This course may not be repeated for additional credits.

Pre-requisites: Minimum grade of C in MATH 1042.

MATH 5012. Introduction to Mathematical Modeling for Teaching. 3 Credit Hours.
In this course, mathematics will be discussed as the language of science. Many students do not have an adequate picture of mathematics: they see it either as a dry formal list of formulas or a dull study of numbers. Mathematics is in fact a network of intriguing and profound ideas that are deeply connected to reality. As a language, mathematics provides penetrating techniques of thought that allow us to analyze physical reality and to look for answers or solutions to some of the most intriguing real-life questions. Students will be asked to read the material in advance and come prepared for class discussion. The in-class activities will be conducted in an inquiry-minded fashion.

Repeatability: This course may not be repeated for additional credits.

Pre-requisites: Minimum grade of C in MATH 1042.

MATH 5013. Geometry for Teaching. 3 Credit Hours.
This class will provide a deep and complete picture of the underlying concepts needed to teach high school geometry. We'll start by learning about the basic axiomatic method, which is fundamental to all of mathematics. We'll learn about the rigid transformations (reflections, rotations, and translations) and the important role that they can play in defining congruence more generally. We'll finish by looking at some important examples of non-Euclidean geometry, where Euclid's famous parallel postulate does not hold.

Repeatability: This course may not be repeated for additional credits.

Pre-requisites: Minimum grade of C in MATH 1042.

MATH 5014. Probability Theory and Applications for Teaching. 3 Credit Hours.
Probability is a fundamental topic with applications in nearly every aspect of life. The goal for this course is to equip the student with a large and diverse set of tools with which to tackle a wide variety of problems, both theory and application based. We will focus on the ideas behind the important topics e.g. conditioning, averages, binomial distribution, and explain their origins and applications. This will equip the student to teach their own students this material with an emphasis on the "why", which is essential to maintaining attentiveness.

Repeatability: This course may not be repeated for additional credits.

Pre-requisites: Minimum grade of C in MATH 1042.

MATH 5015. Modern Algebra for Teaching. 3 Credit Hours.
Students will understand the integers and polynomial rings over a field as being specific examples of rings. The idea of quotient spaces will be emphasized with the particular examples of the integers modulo n and factor rings of polynomial rings illustrating and introducing the concept. Moreover, the ability to read and to construct well-written and correct mathematical proofs on these topics is an overarching goal of the course. Written communication skills will also be emphasized.

Repeatability: This course may not be repeated for additional credits.

Pre-requisites: Minimum grade of C in MATH 2111.

MATH 5016. Mathematical Analysis for Teaching. 3 Credit Hours.
This course will start with a discussion of the basic topology of the real line and the creation of the basic tools using the completeness axiom. From there, the course will proceed to sequences and series, limits, continuity, differentiation, Riemann integration, and Taylor series representations of functions.

Repeatability: This course may not be repeated for additional credits.

Pre-requisites: Minimum grade of C in MATH 2043.

MATH 5017. Number Theory and Proof for Teaching. 3 Credit Hours.
In this course, we encounter and explore fundamental ideas in number theory. Basic properties of the integers and their two principal operations, addition and multiplication, will form the starting point of our study. Along the way, the course will introduce some basic logic and the rigorous notion of mathematical proof, including mathematical induction, in the context of number theory. Through this elementary foundation, students will experience the richness of mathematics: proof going back as far as Euclid, examples of elementary yet still unproven conjectures, and results that are easy to state and understand but require extremely complicated proofs.

Repeatability: This course may not be repeated for additional credits.

Pre-requisites: Minimum grade of C in MATH 1042.

MATH 5032. Stochastic Calculus. 3 Credit Hours.
This course is an introduction to stochastic calculus based on Brownian motion and Gaussian processes, covering stochastic differential equations as well as applications to option pricing in finance. Concepts and results are illustrated with examples and numerical projects.

Repeatability: This course may not be repeated for additional credits.

MATH 5033. Introduction to Stochastic Processes. 3 Credit Hours.
This course is an introduction to some of the basic models, concepts, results and techniques in the study of stochastic processes and touches upon applications along the way. It covers a large selection of the following topics: finite- and countable-state Markov chains, Poisson and birth-and-death processes, optimal stopping, martingales, renewal processes, Markov chain algorithms, and introduction to Brownian motion.

Repeatability: This course may not be repeated for additional credits.

MATH 5034. High-Dimensional Probability. 3 Credit Hours.
This course provides a self-contained introduction to the area of high-dimensional probability and statistics from a non-asymptotic perspective, aimed at students across the mathematical sciences. It will include a focus on core methodology and theory (tail bounds, concentration of measure, random matrices, random graphs and networks) as well as in-depth exploration of various applications (to statistical learning theory, sparse linear and graphical models, community detection, as examples).

Repeatability: This course may not be repeated for additional credits.

MATH 5041. Concepts of Analysis I. 3 Credit Hours.
This is a first semester course in basic real analysis. Topics include the real number system and the completeness property, ordered fields, topology of metric spaces, sequences and series, limits of functions and continuity, and differentiation.

Repeatability: This course may not be repeated for additional credits.

MATH 5042. Concepts of Analysis II. 3 Credit Hours.
This is a second semester course in real analysis, representing a continuation of MATH 5041. Topics include the Riemann integral, infinite series and convergence tests, sequences of functions, uniform convergence, power and Taylor series and operations with them, differentiability of vector valued functions, inverse and implicit function theorems, differential forms, vector analysis, and formula of change of variables in multiple integrals.

Repeatability: This course may not be repeated for additional credits.

Pre-requisites: Minimum grade of B- in MATH 5041.

MATH 5043. Numerical Analysis. 3 Credit Hours.
This course provides a graduate level introduction to classical and modern methods for fundamental problems in computational science and engineering, including approximation and interpolation, numerical integration/quadrature, direct methods for systems of equations, and solution of systems of nonlinear equations. A rigorous mathematical approach to these topics is taken, including floating point arithmetic, error analysis, conditioning and stability, and convergence theorems. The course is accessible to graduate students from all areas of science and engineering interested in a mathematical foundation for the listed computational methods.

Repeatability: This course may not be repeated for additional credits.

MATH 5044. Numerical Methods for Ordinary Differential Equations. 3 Credit Hours.
This course introduces numerical methods for ordinary differential equations, including explicit, implicit, and semi-implicit time stepping methods (such as Runge-Kutta, multistep, and Taylor series methods). A rigorous mathematical basis is established, including convergence, stability, and error estimators. Critical challenges commonplace in applications, like stiff problems, and specialized time stepping methods, are also presented.

Repeatability: This course may not be repeated for additional credits.

MATH 5045. Ordinary Differential Equations. 3 Credit Hours.
The course covers existence and uniqueness theorems for ordinary differential equations (ODEs), along with continuous and smooth dependence on initial conditions and parameters, assuming familiarity with the material of advanced calculus. Topics include linear differential equations, their qualitative and asymptotic behavior, and the analysis of isolated singularities. The course also introduces nonlinear equations and Sturm-Liouville problems, emphasizing both theoretical aspects and applications. Basic methods for the numerical solution of ODEs are presented, including stability and convergence considerations.

Repeatability: This course may not be repeated for additional credits.

MATH 5057. Applied Partial Differential Equations and Optimization. 3 Credit Hours.
This course introduces and studies partial differential equations (PDEs) central to applied mathematics and related fields, arising from continuum mechanics and optimization. Material includes continuum mechanics, methods for linear PDEs, calculus of variations, as well as basic constrained optimization and control. Course topics have a wide applicability to the sciences and engineering.

Repeatability: This course may not be repeated for additional credits.

MATH 5058. Fundamentals of Mathematical Modeling. 3 Credit Hours.
This course introduces fundamental principles of mathematical modeling. Basics of constructing and analyzing models, including scaling and asymptotics, are studied in large part through dynamical systems and their applications. Examples from many areas across the sciences and engineering disciplines are central to this course.

Repeatability: This course may not be repeated for additional credits.

MATH 5061. Fundamentals of Computer Programming for Scientists and Engineers. 4 Credit Hours.
Scientists and engineers use computers for a multitude of purposes. Even with ready-to-use applications, some amount of computer programming is commonly required to adapt to changing technology while attaining the rigorous standards of each specific discipline. This course focuses on fundamental computer programming constructs, introducing the languages Python, C++ and Fortran. Through lectures and intensive exercises students will learn to implement fundamental mathematical constructs and solve basic programming problems relevant to scientific applications. The course briefly reviews also the Linux environment, its software development tools and language interoperability. For each programming language, the course focuses on constructs and syntax designed for performance and numerical accuracy, in connection with methods from applied science, mathematics and engineering. The students taking the course are expected to have sufficient mathematical maturity, as evidenced, for example, by having completed an undergraduate Calculus sequence. The majority of the grade is determined by a mid-term and a final exam, both including a combination of questionnaires and supervised programming assignments.

Repeatability: This course may not be repeated for additional credits.

MATH 5062. High Performance Computer Programming for Scientific Modeling. 3 Credit Hours.
This course will provide theory and hands-on experience programming high performance computers for the solution of scientific modeling problems. This includes in particular problems arising from the discretizations of differential equations. Topics covered include domain decomposition and mesh partitioning, quantifying the computation and communication cost, communication avoidance methods, Monte Carlo methods, multithreading, benchmarking and optimization of the parallel computations.

Repeatability: This course may not be repeated for additional credits.

Pre-requisites: Minimum grade of B- in MATH 5061.

MATH 5063. Introduction to High-Performance Computing Technology for Scientists. 4 Credit Hours.
This course is an introduction to the technology used in Linux clusters and supercomputers dedicated to calculations in applied science and engineering. The basic architecture of modern computers (processing units, memory, storage, operating system) is briefly reviewed, emphasizing the role and performance impact of each element in numerical computation. The core of the course focuses on setup and management of computer hardware specialized for scientific computing, and on its impact on commonly used strategies and methods for scientific computation. The material is organized in a combination of lectures and hands-on exercises, using computer hardware hosted at local facilities as well as virtualized resources. The majority of the grade is determined by a mid-term and a final exam, both including a combination of questionnaires and identification of the most efficient solution to common numerical problems.

Repeatability: This course may not be repeated for additional credits.

Pre-requisites: Minimum grade of B- in MATH 5061 (may be taken concurrently)

MATH 5065. Topology. 3 Credit Hours.
This course covers the fundamentals of metric spaces and topological spaces. Core topics include continuity, compactness, connectedness, and convergence. Time permitting, the course will include the classification of compact surfaces and an introduction to algebraic topology, including fundamental groups and covering spaces.

Repeatability: This course may not be repeated for additional credits.

MATH 5066. Mathematical Methods for High Performance Computing. 3 Credit Hours.
This course presents mathematical methods for the solution of a variety of discrete and algebraic problems which are at the core of many scientific and engineering applications. The methods covered are especially tailored for high performance computing. Topics include large matrix computations, graphs and networks, fast Fourier transforms, geometric and algebraic multi-grid methods, and constrained optimization.

Repeatability: This course may not be repeated for additional credits.

Pre-requisites: Minimum grade of B- in MATH 5061, MATH 5062, and MATH 5063.

MATH 5067. Introduction to Abstract Algebra I. 3 Credit Hours.
This is the first semester in a year-long introduction to modern algebra. It is a thorough introduction to the theory of groups and rings.

Repeatability: This course may not be repeated for additional credits.

MATH 5068. Introduction to Abstract Algebra II. 3 Credit Hours.
This is the second semester in a year-long introduction to modern algebra. Topics come from the theory of rings, fields, modules and Galois theory.

Repeatability: This course may not be repeated for additional credits.

Pre-requisites: Minimum grade of B- in MATH 5067.

MATH 5071. Mathematical Aspects of Cryptography. 3 Credit Hours.
This course on the mathematical aspects of cryptography proceeds in four parts. In Part 1, we go over groups, rings, and finite fields. Part 2 is devoted to symmetric key cryptosystems, including both classical cryptosystems (affine cipher, substitution cipher, Hill cipher) and modern cryptosystems, e.g., the Advanced Encryption Standard (AES, Rijndael). Part 3 is devoted to aspects of elementary number theory related to cryptography. Part 4 is devoted to public key cryptosystems. In this part, we learn the discrete logarithm problem, the Diffie-Hellman key exchange, the Pohlig-Hellman algorithm and the collision algorithm, the ElGamal public key cryptosystem, the Rivest-Shamir-Adleman (RSA) public key cryptosystem, and attacks on RSA. The course involves programming problems and a study project.

Repeatability: This course may not be repeated for additional credits.

MATH 8001. Candidates Seminar. 1 to 3 Credit Hour.
Challenging problems from many different areas of mathematics are posed and discussed.

Repeatability: This course may be repeated for additional credit.

MATH 8002. Candidates Seminar. 1 to 3 Credit Hour.
Challenging problems from many different areas of mathematics are posed and discussed.

Repeatability: This course may be repeated for additional credit.

MATH 8011. Abstract Algebra I. 3 Credit Hours.
Groups, rings, modules, fields; Galois theory; linear algebra.

Repeatability: This course may not be repeated for additional credits.

MATH 8012. Abstract Algebra II. 3 Credit Hours.
Groups, rings, modules, fields; Galois theory; linear algebra.

Repeatability: This course may not be repeated for additional credits.

Pre-requisites: Minimum grade of B- in MATH 8011.

MATH 8013. Numerical Linear Algebra I. 3 Credit Hours.
The syllabus includes iterative methods, classical methods, nonnegative matrices. Semi-iterative methods. Multigrid methods. Conjugate gradient methods. Preconditioning. Domain decomposition. Direct Methods. Sparse Matrix techniques. Graph theory. Eigenvalue Problems.

Repeatability: This course may not be repeated for additional credits.

MATH 8014. Numerical Linear Algebra II. 3 Credit Hours.
The syllabus includes iterative methods, classical methods, nonnegative matrices. Semi-iterative methods. Multigrid methods. Conjugate gradient methods. Preconditioning. Domain decomposition. Direct Methods. Sparse Matrix techniques. Graph theory. Eigenvalue Problems.

Repeatability: This course may not be repeated for additional credits.

Pre-requisites: Minimum grade of B- in MATH 8013.

MATH 8023. Numerical Differential Equations I. 3 Credit Hours.
Analysis and numerical solution of ordinary and partial differential equations. Elliptic, parabolic and hyperbolic systems. Constant and variable coefficients. Finite difference methods. Finite element methods. Convergence analysis. Practical applications.

Repeatability: This course may not be repeated for additional credits.

MATH 8024. Numerical Differential Equations II. 3 Credit Hours.
Analysis and numerical solution of ordinary and partial differential equations. Elliptic, parabolic and hyperbolic systems. Constant and variable coefficients. Finite difference methods. Finite element methods. Convergence analysis. Practical applications.

Repeatability: This course may not be repeated for additional credits.

Pre-requisites: Minimum grade of B- in MATH 8023.

MATH 8031. Probability Theory. 3 Credit Hours.
With a rigorous approach the course covers the axioms, random variables, expectation and variance. Limit theorems are developed through characteristic functions.

Repeatability: This course may not be repeated for additional credits.

MATH 8032. Stochastic Processes. 3 Credit Hours.
Random sequences and functions; linear theory; limit theorems; Markov processes; branching processes; queuing processes.

Repeatability: This course may not be repeated for additional credits.

Pre-requisites: Minimum grade of B- in MATH 8031.

MATH 8041. Real Analysis I. 3 Credit Hours.
The syllabus coincides with the syllabus for the Ph.D. Examination in Real Analysis.

Repeatability: This course may not be repeated for additional credits.

MATH 8042. Real Analysis II. 3 Credit Hours.
The syllabus coincides with the syllabus for the Ph.D. Examination in Real Analysis.

Repeatability: This course may not be repeated for additional credits.

Pre-requisites: Minimum grade of B- in MATH 8041.

MATH 8051. Functions of a Complex Variable I. 3 Credit Hours.
Analytic functions. Conformal mapping. Analytic continuation. Topics in univalent functions, elliptic functions, Riemann surfaces, analytic number theory. Nevanlinna theory, several complex variables.

Repeatability: This course may not be repeated for additional credits.

MATH 8052. Functions of a Complex Variable II. 3 Credit Hours.
Analytic functions. Conformal mapping. Analytic continuation. Topics in univalent functions, elliptic functions, Riemann surfaces, analytic number theory. Nevanlinna theory, several complex variables.

Repeatability: This course may not be repeated for additional credits.

Pre-requisites: Minimum grade of B- in MATH 8051.

MATH 8061. Differential Geometry and Topology I. 3 Credit Hours.
Elementary theory of smooth manifolds. Singular cohomology and DeRham's theorem. Fundamental group and covering spaces. Hodge theory.

Repeatability: This course may not be repeated for additional credits.

MATH 8062. Differential Geometry and Topology II. 3 Credit Hours.
Repeatability: This course may not be repeated for additional credits.

Pre-requisites: Minimum grade of B- in MATH 8061.

MATH 8107. Mathematical Modeling for Science, Engineering, and Industry. 3 Credit Hours.
In this course, students work in groups on projects that arise in industry, engineering, or in other disciplines of science. In addition to being advised by the course instructors, in all projects an external partner is present. The problems are formulated in non-mathematical language, and the final results need to be formulated in a language accessible to the external partner. This means in particular that the mathematical and computational methods must be selected or created by the students themselves. Students disseminate their progress and achievements in weekly presentations, a mid-term and a final project report, and a final presentation. Group work with and without the instructors' involvement is a crucial component in this course.

Repeatability: This course may not be repeated for additional credits.

Pre-requisites: Minimum grade of B- in MATH 8007 and MATH 8008.

MATH 8141. Partial Differential Equations I. 3 Credit Hours.
The classical theory of partial differential equations. Elliptic, parabolic, and hyperbolic operations.

Repeatability: This course may not be repeated for additional credits.

MATH 8142. Partial Differential Equations II. 3 Credit Hours.
The classical theory of partial differential equations. Elliptic, parabolic, and hyperbolic operations.

Repeatability: This course may not be repeated for additional credits.

Pre-requisites: Minimum grade of B- in MATH 8141.

MATH 8161. Topology. 3 Credit Hours.
Point set topology through the Urysohn Metrization Theorem; fundamental group and covering spaces. Differential forms; the DeRham groups.

Repeatability: This course may not be repeated for additional credits.

Pre-requisites: Minimum grade of B- in MATH 5041.

MATH 8200. Topics in Applied Mathematics. 3 Credit Hours.
Variable topics, such as control theory and transform theory, will be treated.

Repeatability: This course may be repeated for additional credit.

MATH 8210. Topics in Applied Mathematics II. 3 Credit Hours.
Variable topics, such as control theory and transform theory, will be treated.

Repeatability: This course may be repeated for additional credit.

MATH 8700. Topics Computer Program. 3 Credit Hours.
Repeatability: This course may be repeated for additional credit.

MATH 8710. Topics Computer Program. 3 Credit Hours.
Repeatability: This course may be repeated for additional credit.

MATH 8981. Graduate Development Seminar. 1 Credit Hour.
This course aims to familiarize first-year PhD students with the structure of a PhD in Mathematics. A significant focus of the course is professional development, wherein students learn about important milestones in the program and are trained in the related responsibilities. Students enrolled in this course must attend at least one seminar or colloquium per week, in order to be exposed to research-level mathematics and best practices for communicating mathematics. The seminar itself features a weekly discussion on a topic of interest, led by the Director of Graduate Studies and/or a senior TA. Topics covered in the seminar should include: Basics of departmental structure; effective study techniques for graduate courses and qualifying exams; best practices for professional conduct; creating a professional webpage; written and oral communication of research-level mathematics; research topics studied by faculty in the department; the process of finding a PhD advisor, e.g. through independent study courses; organizing PhD studies with perspective of post-PhD career goals; finding and applying for summer internships in industry and education; and applying for post-PhD employment, in and out of academia.

Repeatability: This course may not be repeated for additional credits.

MATH 8985. Teaching in Higher Education. 1 to 3 Credit Hour.
This course is required for any student seeking Temple's Teaching in Higher Education Certificate. The course focuses on the research on learning theory and the best teaching practices, with the aim of preparing students for effective higher education teaching. All educational topics will be considered through the lens of teaching mathematics and quantitative thinking.

Repeatability: This course may not be repeated for additional credits.

MATH 9000. Topics in Number Theory I. 3 Credit Hours.
Analytic and algebraic number theory. Classical results and methods and special topics such as partition theory, asymptotic, Zeta functions, transcendence, modular functions.

Repeatability: This course may be repeated for additional credit.

MATH 9003. Modular Functions. 3 Credit Hours.
This course focuses upon the modular group and its subgroups, the corresponding fundamental region and their invariant functions. Included will be a discussion of the basic properties of modular forms and their construction by means of Eisenstein and Poincar © series and theta series. Other topics: the Hecke correspondence between modular forms and Dirichlet series with functional equations, the Peterson inner product, the Hecke's operators. Emphasis will be placed upon applications to number theory. References: M. Knopp, "Modular functions in analytic number theory"; J. Lehner, "A short course in automorphic forms"; B. Schoeneberg, "Elliptic modular forms."

Repeatability: This course may not be repeated for additional credits.

MATH 9004. Modular Functions. 3 Credit Hours.
This course focuses upon the modular group and its subgroups, the corresponding fundamental region and their invariant functions. Included will be a discussion of the basic properties of modular forms and their construction by means of Eisenstein and Poincar © series and theta series. Other topics: the Hecke correspondence between modular forms and Dirichlet series with functional equations, the Peterson inner product, the Hecke's operators. Emphasis will be placed upon applications to number theory. References: M. Knopp, "Modular functions in analytic number theory"; J. Lehner, "A short course in automorphic forms"; B. Schoeneberg, "Elliptic modular forms."

Repeatability: This course may not be repeated for additional credits.

MATH 9005. Combinatorial Mathematics. 3 Credit Hours.
Topics include: Enumeration, Trees, Graphs, Codes, Matchings, Designs, Chromatic Polynomials, Coloring, Networks.

Repeatability: This course may not be repeated for additional credits.

MATH 9010. Topics in Number Theory II. 3 Credit Hours.
Analytic and algebraic number theory. Classical results and methods and special topics such as partition theory, asymptotic, Zeta functions, transcendence, modular functions.

Repeatability: This course may be repeated for additional credit.

MATH 9011. Homological Algebra. 3 Credit Hours.
Students will learn fundamental notions of homological algebra such as chain complexes, Abelian categories, derived functors, and spectral sequences. A portion of this course is also devoted to rudiments of category theory. Students will learn how to apply constructions of homological algebra and category theory to questions from abstract algebra, topology and deformation theory.

Repeatability: This course may not be repeated for additional credits.

Pre-requisites: Minimum grade of B- in MATH 8011 and MATH 8012.

MATH 9012. Representation Theory I. 3 Credit Hours.
This is the first semester of a two-semester course on the principal methods and results of algebraic representation theory. The course will start with an introduction to the fundamental notions, tools and general results of representation theory in the setting of associative algebras. This will be followed by a thorough coverage of the classical representation theory of finite groups over an algebraically closed field of characteristic zero. If time permits, then the semester will conclude with a brief introductory discussion of the representation theory of the general linear group.

Repeatability: This course may not be repeated for additional credits.

Pre-requisites: Minimum grade of B- in MATH 8011 and MATH 8012.

MATH 9013. Representation Theory II. 3 Credit Hours.
This is the second part of a two-semester course sequence on the principal methods and results of algebraic representation theory. The main focus will be on representations of finite-dimensional Lie algebras, with particular emphasis on the case of semisimple Lie algebras. Time permitting, the course will conclude with an introduction to the representation theory of Hopf algebras.

Repeatability: This course may not be repeated for additional credits.

Pre-requisites: Minimum grade of B- in MATH 9012.

MATH 9014. Commutative Algebra and Algebraic Geometry I. 3 Credit Hours.
This is the first semester of a two-semester course on the fundamental concepts of commutative algebra and classical as well as modern algebraic geometry. Topics for the first semester include: ideals of commutative rings, modules, Noetherian and Artinian rings, Noether normalization, Hilbert's Nullstellensatz, rings of fractions, primary decomposition, discrete valuation rings and the rudiments of dimension theory.

Repeatability: This course may not be repeated for additional credits.

Pre-requisites: Minimum grade of B- in MATH 8011 and MATH 8012.

MATH 9015. Commutative Algebra and Algebraic Geometry II. 3 Credit Hours.
This is the second semester of a two-semester course on the fundamental concepts of commutative algebra and classical as well as modern algebraic geometry. Topics for the second semester include: affine and projective varieties, morphisms of algebraic varieties, birational equivalence, and basic intersection theory. In the second semester, students will also learn about schemes, morphisms of schemes, coherent sheaves, and divisors.

Repeatability: This course may not be repeated for additional credits.

Pre-requisites: Minimum grade of B- in MATH 9014.

MATH 9021. Riemannian Geometry. 3 Credit Hours.
The main goal of this one-semester course is to provide a solid introduction to the two central concepts of Riemannian Geometry, namely, geodesics and curvature and their relationship. After taking this course, students will have an intimate acquaintance with the tools and concepts that are needed for pursuing research in Riemannian Geometry or applying its ideas to other fields of mathematics such as analysis, topology, and algebraic geometry. The topics covered include Riemannian metrics, Riemannian connections, geodesics, curvature (sectional, Ricci, and scalar curvatures), the Jacobi equation, the second fundamental form, and global results such as the Gauss-Bonnet Theorem, the theorems of Hopf-Rinow and Hadamard, variations of energy, the theorems of Bonnet-Myers and of Synge-Weinstein, and the Rauch comparison theorem.

Repeatability: This course may not be repeated for additional credits.

Pre-requisites: Minimum grade of B- in MATH 8061 and MATH 8062 (may be taken concurrently)

MATH 9023. Knot Theory and Low-Dimensional Topology I. 3 Credit Hours.
This is the first semester of a year-long course surveying the modern theory of knots and providing an introduction to some fundamental results and techniques of low-dimensional topology. The course will start at the very beginning of knot theory; it will then proceed to several classical knot invariants (Alexander, Jones, HOMFLY polynomials). The first semester will also touch on braid groups and mapping class groups, and use these groups to show that every (closed, orientable) 3-manifold can be constructed via knots.

Repeatability: This course may not be repeated for additional credits.

Pre-requisites: Minimum grade of B- in MATH 8061 and MATH 8062.

MATH 9024. Knot Theory and Low-Dimensional Topology II. 3 Credit Hours.
This is the second semester of a year-long course surveying the modern theory of knots and providing an introduction to some fundamental results and techniques of low-dimensional topology. This course will continue the development of knot invariants begun during the first semester, in particular exploring the connection between knots and braid groups. It will also use Dehn surgery techniques to extend construct quantum invariants of closed 3-dimensional manifolds. Finally, the course will survey several results in 4-dimensional topology and their connection to knot theory.

Repeatability: This course may not be repeated for additional credits.

Pre-requisites: Minimum grade of B- in MATH 9023.

MATH 9031. Advanced Probability Theory. 3 Credit Hours.
This course is a continuation of MATH 8031 and is based on measure theory. It covers advanced topics in probability theory: martingales, Brownian motion, Markov chains, continuous time Markov processes, ergodic theory and their applications.

Repeatability: This course may not be repeated for additional credits.

MATH 9041. Functional Analysis I. 3 Credit Hours.
Topics covered include Banach and Hilbert spaces, Banach-Steinhaus theorem, Hahn-Banach theorem, Stone-Weierstrass theorem, Operator theory, self-adjointness, compactness. Also covered are Sobolev spaces, embedding theorems, Schwartz distributions, Paley-Wiener theory. If time permits, Banach and C algebras will be covered.

Repeatability: This course may not be repeated for additional credits.

Pre-requisites: Minimum grade of B- in MATH 8041 and MATH 8042.

MATH 9042. Functional Analysis II. 3 Credit Hours.
Topics covered include: Banach and Hilbert spaces, Banach-Steinhaus theorem, Hahn-Banach theorem, Stone-Weierstrass theorem, Operator theory, self-adjointness, compactness. Also covered are Sobolev spaces, embedding theorems, Schwartz distributions, Paley-Wiener theory. If time permits, Banach and C algebras will be covered.

Repeatability: This course may not be repeated for additional credits.

Pre-requisites: Minimum grade of B- in MATH 9041.

MATH 9043. Calculus of Variations. 3 Credit Hours.
First variation and Euler-Lagrange equations. Null-Lagrangians and the Caratheodory's "Royal Road". Geodesic coverings, the eikonal and the Hamilton-Jacobi equation. Second variation and Jacobi's theory of conjugate points. Strong variations and Weierstrass E-function. Hamiltonian formalism and convex duality. Hilbert's invariant integral.

Repeatability: This course may not be repeated for additional credits.

MATH 9044. Harmonic Analysis. 3 Credit Hours.
A year long course to explore the real-variable techniques developed in Harmonic Analysis to study smoothness properties of functions and the behavior of certain spaces under the action of some operators. These techniques are also essential in many applications to PDE's and several complex variables. Offered every two years.

Repeatability: This course may not be repeated for additional credits.

MATH 9051. Several Complex Variables I. 3 Credit Hours.
Holomorphic functions of several complex variables, domains of holomorphy, pseudoconvexity, analytic varieties, CR manifolds.

Repeatability: This course may not be repeated for additional credits.

Pre-requisites: Minimum grade of B- in MATH 8051 and MATH 8052.

MATH 9052. Several Complex Variables II. 3 Credit Hours.
Holomorphic functions of several complex variables, domains of holomorphy, pseudoconvexity, analytic varieties, CR manifolds.

Repeatability: This course may not be repeated for additional credits.

Pre-requisites: Minimum grade of B- in MATH 9051.

MATH 9053. Harmonic Analysis. 3 Credit Hours.
A year long course to explore the real-variable techniques developed in Harmonic Analysis to study smoothness properties of functions and the behavior of certain spaces under the action of some operators. These techniques are also essential in many applications to PDE's and several complex variables. Offered every two years.

Repeatability: This course may not be repeated for additional credits.

MATH 9061. Lie Groups. 3 Credit Hours.
This course develops Lie theory from the ground up. Starting with basic definitions of Lie group-manifolds and Lie algebras, the course develops structure theory, analytic and algebraic aspects, and representation theory. Interactions with other fields, e.g., differential equations and geometry are also discussed.

Repeatability: This course may not be repeated for additional credits.

MATH 9062. Lie Groups. 3 Credit Hours.
This course develops Lie theory from the ground up. Starting with basic definitions of Lie group-manifolds and Lie algebras, the course develops structure theory, analytic and algebraic aspects, and representation theory. Interactions with other fields, e.g., differential equations and geometry are also discussed.

Repeatability: This course may not be repeated for additional credits.

MATH 9063. Riemann Surfaces. 3 Credit Hours.
Introduction to differential geometry, Riemannian manifolds and Hodge theory; classification of complex structures of oriented two-manifolds as conformal classes of Riemannian metrics; covering spaces and the uniformization theorem; the moduli space of the torus; the Riemann-Roch theorem for compact Riemann surfaces; interpretation of the Riemann-Roch theorem as the index of an elliptic operator.

Repeatability: This course may not be repeated for additional credits.

MATH 9064. Riemann Surfaces. 3 Credit Hours.
Moduli and Teichmueller spaces for compact Riemann surfaces; introduction to modular forms; embedding of compact Riemann surfaces in complex projective spaces. Branched coverings and maps onto the Riemann sphere.

Repeatability: This course may not be repeated for additional credits.

MATH 9071. Differential Topology. 3 Credit Hours.
Moduli and Teichmueller spaces for compact Riemann surfaces; introduction to modular forms; embedding of compact Riemann surfaces in complex projective spaces. Branched coverings and maps onto the Riemann sphere.

Repeatability: This course may not be repeated for additional credits.

MATH 9072. Differential Topology. 3 Credit Hours.
Topics and emphasis may vary depending on instructor and may include surgery, handlebodies, cobordism; topological manifolds with smooth structure, manifolds with more than one smooth structures; topology of vector bundles, characteristic classes, index theorem.

Repeatability: This course may not be repeated for additional credits.

MATH 9073. Geometric Group Theory. 3 Credit Hours.
This semester-long course will survey the rapidly expanding field of geometric group theory, focusing on the role played by negative curvature. We will begin with classical combinatorial techniques used to construct and study infinite discrete groups. After introducing basic concepts in coarse geometry, we will turn our attention to Gromov's notion of hyperbolic groups. In addition to studying geometric, algebraic, and algorithmic properties of these groups, we will keep an eye towards several generalizations of hyperbolicity that have recently played a large role in understanding many geometrically significant groups. As examples, we will also touch on the study of mapping class groups, outer automorphism groups of free groups, and cubical groups.

Repeatability: This course may not be repeated for additional credits.

Pre-requisites: Minimum grade of B- in MATH 8061 and MATH 8062.

MATH 9082. Independent Study. 1 to 3 Credit Hour.
Independent research supervised by a Mathematics faculty member.

Repeatability: This course may be repeated for additional credit.

MATH 9083. Independent Study. 1 to 3 Credit Hour.
Independent research supervised by a Mathematics faculty member.

Repeatability: This course may be repeated for additional credit.

MATH 9100. Topics in Algebra. 3 Credit Hours.
Variable topics in theory of commutative and non-commutative rings, groups, algebraic number theory, algebraic geometry.

Repeatability: This course may be repeated for additional credit.

MATH 9110. Topics in Algebra. 3 Credit Hours.
Variable topics in theory of commutative and non-commutative rings, groups, algebraic number theory, algebraic geometry.

Repeatability: This course may be repeated for additional credit.

MATH 9120. Seminar in Algebra. 3 Credit Hours.
The seminar aims to lead participating students up to the frontier of current research in algebra. The typical formats are single lectures or short series of lectures by students or the instructor on various topics in algebra, including noncommutative algebra, representation theory, group theory, operads and connections to mathematical physics. Occasionally, slightly longer mini-courses are presented in the framework of the seminar or an entire semester is devoted to a single topic of particular interest.

Repeatability: This course may be repeated for additional credit.

MATH 9200. Topics in Numerical Analysis. 3 Credit Hours.
These courses cover some basic, as well as advanced topics in numerical analysis. The topics can be changed from time to time. The usual topics include: scientific computing, numerical methods for differential equations, computational fluid dynamics, Monte Carlo simulation, Optimization, Spare matrices, Fast Fourier transform and applications, etc.

Repeatability: This course may be repeated for additional credit.

MATH 9210. Topics in Numerical Analysis. 3 Credit Hours.
These courses cover some basic, as well as advanced topics in numerical analysis. The topics can be changed from time to time. The usual topics include: scientific computing, numerical methods for differential equations, computational fluid dynamics, Monte Carlo simulation, Optimization, Spare matrices, Fast Fourier transform and applications, etc.

Repeatability: This course may be repeated for additional credit.

MATH 9300. Seminar in Probability. 3 Credit Hours.
Research topics related to probability theory are presented in the seminar. Topics vary depending on the interests of the students and the instructor. Current topics include stochastic calculus with applications in mathematical finance, statistical mechanics, interacting particle systems, percolation, and probability models in mathematical physics.

Repeatability: This course may be repeated for additional credit.

MATH 9310. Seminar in Probability. 3 Credit Hours.
Research topics related to probability theory are presented in the seminar. Topics vary depending on the interests of the students and the instructor. Current topics include stochastic calculus with applications in mathematical finance, statistical mechanics, interacting particle systems, percolation, and probability models in mathematical physics.

Repeatability: This course may be repeated for additional credit.

MATH 9400. Topics in Analysis. 3 Credit Hours.
Variable content course.

Repeatability: This course may be repeated for additional credit.

MATH 9410. Topics in Functional Analysis. 3 Credit Hours.
This is a year-long sequence. The content varies from time to time depending on the interests of the students. Typical topics include some of the following: pseudodifferential operators, Fourier integral operators, singular integral operators, applications to partial differential equations.

Repeatability: This course may be repeated for additional credit.

MATH 9420. Topics in Differential Equations II. 3 Credit Hours.
This is a year-long sequence. Topics covered may include the theory of elliptic partial differential equations in divergence form and non-divergence form, and nonlinear PDEs. These courses may also focus on pseudodifferential operators and Fourier integral operators.

Repeatability: This course may be repeated for additional credit.

MATH 9500. Topics in Differential Geometry and Topology I. 3 Credit Hours.
Variable topics in geometric topology and related areas. Topics include: surfaces and their diffeomorphisms, mapping class groups, braids, 3-dimensional manifolds, geometric structures on manifolds, and group actions on geometric objects.

Repeatability: This course may be repeated for additional credit.

Pre-requisites: Minimum grade of B- in MATH 8061 and MATH 8062.

MATH 9510. Topics in Differential Geometry and Topology II. 3 Credit Hours.
Variable topics in geometric topology and related areas. Topics include: surfaces and their diffeomorphisms, mapping class groups, braids, 3-dimensional manifolds, geometric structures on manifolds, and group actions on geometric objects.

Repeatability: This course may be repeated for additional credit.

Pre-requisites: Minimum grade of B- in MATH 8061 and MATH 8062.

MATH 9991. Master's Research Projects. 1 to 6 Credit Hour.
Short-term, limited research project or laboratory project in the field. This course is not the capstone project course, nor can it be used for thesis based research. The course is for master's students only, including PSM, MA or MS. This class will not confer full-time program status unless nine credits are taken.

Repeatability: This course may be repeated for additional credit.

MATH 9994. Preliminary Examination Preparation. 1 to 6 Credit Hour.
This course is required for students who are preparing for the preliminary or candidacy examination. Students should enroll after coursework is completed or when preparing for the candidacy exam until the time that the preliminary or candidacy examination is completed. This course will confer full-time status at the minimum credit hour registration limit of one credit. All students must complete a minimum of one credit of this course. Students must complete a total of 6 credit hours of 9994, 9998 and 9999.

Repeatability: This course may be repeated for additional credit.

MATH 9995. Capstone Project. 1 to 6 Credit Hour.
Capstone project for master's students including students in PSM, MA or MS. This class will provide full-time status. Students in PSM programs need to register for at least one credit of this course to fulfill program requirements. Additional credits may be required for specific programs. This course will confer full-time status at the minimum credit hour registration limit of one credit.

Repeatability: This course may be repeated for additional credit.

MATH 9996. Master's Thesis Research. 1 to 6 Credit Hour.
Course for master's thesis research. Only intended for students in thesis bearing master's programs. A minimum of one credit is required. This course will confer full-time status at the minimum credit hour registration limit of one credit.

Repeatability: This course may be repeated for additional credit.

MATH 9998. Pre-Dissertation Research / Elevation to Candidacy. 1 to 6 Credit Hour.
This course is intended for students who are performing research prior to candidacy. Students can register for this course after required courses are completed. This course will confer full-time status at the minimum credit hour registration limit of one credit. Students must be registered for this course during the semester that they are to be elevated to candidacy examination. Students must complete a total of 6 credit hours of 9994, 9998 and 9999.

Repeatability: This course may be repeated for additional credit.

MATH 9999. Dissertation Research. 1 to 6 Credit Hour.
The course is for Ph.D. students who have been elevated to candidacy. During the course of their candidacy students must complete a minimum of two credits of dissertation research. This course will confer full-time status at the minimum credit hour registration limit of one credit. Students must complete a total of 6 credit hours of 9994, 9998 and 9999.

Repeatability: This course may be repeated for additional credit.