

# MATHEMATICS (MATH)

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**MATH 001. Elementary Algebra. 0 Hours.**

Semester course; 3 lecture or 3 laboratory/tutorial hours. No credit. Prerequisite: permission of the department chair. The purpose of this course is to provide laboratory and tutorial instruction for those seeking remediation or review of high school algebra. Topics include basic properties of real numbers, operations with algebraic expressions, solution of equations and inequalities, exponents and radicals, introduction to functions and graphing.

**MATH 121. Perspective Geometry. 1 Hour.**

Short course (5 weeks); 3 lecture hours. 1 credit. Students will examine ways in which Renaissance artists who developed linear perspective in geometry in order to paint scenes realistically influenced the development of mathematics and geometry. Topics covered will include the foundations of projective geometry. Pascal's mystic hexagram, Brianchon's Theorem and duality. A need for higher mathematics will also be introduced and explained. MATH 121-122-123 fulfills the math requirement for art students. The sequence can be taken in any order.

**MATH 122. Tessellations. 1 Hour.**

Short course (5 weeks); 3 lecture hours. 1 credit. Students will examine ways in which mathematics is rooted in both natural philosophy and art by examining tiling theory. Course topics include Penrose tilings, symmetries and various other tessellations. MATH 121-122-123 fulfills the math requirement for art students. The sequence can be taken in any order.

**MATH 123. Visualization. 1 Hour.**

Short course (5 weeks); 3 lecture hours. 1 credit. Students will examine ways in which mathematics has been visualized artistically and will develop their own way to express a mathematical idea. Topics covered will include fractals, knots, minimal surfaces, non-Euclidean geometry and the fourth dimension. MATH 121-122-123 fulfills the math requirement for art students. The sequence can be taken in any order.

**MATH 131. Introduction to Contemporary Mathematics. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisite: satisfactory score on the VCU Mathematics Placement Test within the one-year period immediately preceding the beginning of the course. An exception to this policy is made in the case where the stated alternative prerequisite course has been completed at VCU. Topics include optimization problems, data handling, growth and symmetry, and mathematics with applications in areas of social choice. Major emphasis is on the process of taking a real-world situation, converting the situation to an abstract modeling problem, solving the problem and applying what is learned to the original situation. Does not serve as a prerequisite for MATH 151 or other advanced mathematical sciences courses.

**MATH 141. Algebra with Applications. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisites: one year of high school algebra and satisfactory score on the VCU Mathematics Placement Test within the one-year period immediately preceding the beginning of the course. An exception to this policy is made in the case where the stated alternative prerequisite course has been completed at VCU. Topics include sets, functions, exponents, logarithms, matrix algebra, systems of linear equations, inequalities, binomial theorems, sequences, series, complex numbers and linear programming.

**MATH 151. Precalculus Mathematics. 4 Hours.**

Semester course; 3 lecture and 1 mathematics laboratory/recitation hours. 4 credits. Prerequisite: MATH 141 or satisfactory score on the VCU Mathematics Placement Test within the one-year period immediately preceding the beginning of the course. An exception to this policy is made in the case where the stated alternative prerequisite course has been completed at VCU. Concepts and applications of algebra and trigonometry. Topics include graphics, transformations and inverses of functions; linear, exponential, logarithmic, power, polynomial, rational and trigonometric functions.

**MATH 191. Topics in Mathematics. 1-3 Hours.**

Semester course; 1-3 credits. May be repeated for credit. A study of selected topics in mathematics. For a course to meet the general education requirements it must be stated in the Schedule of Classes. See the Schedule of Classes for specific topics to be offered each semester and prerequisites.

**MATH 200. Calculus with Analytic Geometry. 4 Hours.**

Continuous courses; 4 lecture hours. 4-4 credits. Prerequisite for MATH 200: MATH 151 or satisfactory score on the VCU Mathematics Placement Test within the one-year period immediately preceding the beginning of the course. Prerequisite for MATH 201: completion of MATH 200. Limits, continuity, derivatives, differentials, antiderivatives and definite integrals. Applications of differentiation and integration. Selected topics in analytic geometry. Infinite series.

**MATH 201. Calculus with Analytic Geometry. 4 Hours.**

Continuous courses; 4 lecture hours. 4-4 credits. Prerequisite for MATH 200: MATH 151 or satisfactory score on the VCU Mathematics Placement Test within the one-year period immediately preceding the beginning of the course. Prerequisite for MATH 201: completion of MATH 200. Limits, continuity, derivatives, differentials, antiderivatives and definite integrals. Applications of differentiation and integration. Selected topics in analytic geometry. Infinite series.

**MATH 211. Mathematical Structures. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisite: calculus-level placement on the VCU Mathematics Placement Test within the one-year period immediately preceding enrollment in the course or MATH 151, MATH 200, MATH 201 or MGMT 212. An alternative prerequisite course may be approved at the discretion of the academic adviser. An introduction to mathematical logic and set theory, including applications in Boolean algebras and graph theory.

**MATH 230. Mathematics in Civilization. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. For Honors College students only. The growth, development and far-reaching applications of trigonometry, navigation, cartography, logarithms and algebra through ancient, medieval, post-Renaissance and modern times are explored. Will include methods to solve mathematical problems using various historical procedures and will involve collaboration through group projects.

**MATH 255. Introduction to Computational Mathematics. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisite: MATH 201. (A core course for mathematics/applied mathematics majors.) An introduction to computer algebra systems (CAS) and their use in mathematical, scientific and engineering investigations/computations. Introductory mathematical computer programming using a CAS, including implementation of problem-specific algorithms.

**MATH 291. Topics in Mathematics. 1-3 Hours.**

Semester course; 1-3 credits. May be repeated for credit. A study of selected topics in mathematics. See the Schedule of Classes for specific topics to be offered each semester and prerequisites.

**MATH 300. Introduction to Mathematical Reasoning. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisite: MATH 201. (A core course for mathematics/applied mathematics majors.) An introduction to basic concepts of mathematical reasoning and the writing of proofs in an elementary setting. Direct, indirect and induction proofs. Illustrations of the concepts include basic proofs from mathematical logic, elementary set theory, elementary number theory, number systems, foundations of calculus, relations, equivalence relations, functions and counting with emphasis on combinatorial proofs.

**MATH 301. Differential Equations. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisite: MATH 201. Solutions of ordinary differential equations of first order. Solutions of higher order linear differential equations with constant coefficients and variable coefficients by the methods of undetermined coefficients and variation of parameters, solutions by Laplace transforms and applications.

**MATH 302. Numerical Calculus. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisites: MATH 255 (or knowledge of a programming language/mathematical software package) and MATH 201, or permission of the instructor. An introduction to numerical algorithms for solving systems of linear equations, finding zeroes, numerical differentiation and definite integration, optimization.

**MATH 303. Investigations in Geometry. 3 Hours.**

Semester course; 2 lecture and 3 laboratory hours. 3 credits. Prerequisite: MATH 361. Restricted to students majoring in the liberal studies for early and elementary education in the Bachelor of Interdisciplinary Studies program. A study of topics in Euclidean geometry to include congruence, similarity, measurement, coordinate geometry, symmetry and transformation in both two and three dimensions. These topics will be investigated using manipulatives and computer software.

**MATH 305. Elementary Number Theory. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisite: MATH 300. Divisibility, congruences, Euler phi-function, Fermat's Theorem, primitive roots, Diophantine equations.

**MATH 307. Multivariate Calculus. 4 Hours.**

Semester course; 4 lecture hours. 4 credits. Prerequisite: MATH 201. The calculus of vector-valued functions and of functions of more than one variable. Partial derivatives, multiple integrals, line integrals, surface integrals and curvilinear coordinates. Lagrange multipliers; theorems of Green, Gauss and Stokes. Applications.

**MATH 310. Linear Algebra. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisite: MATH 201. Systems of linear equations, vector spaces, linear dependence, bases, dimensions, linear mappings, matrices, determinants, quadratic forms, orthogonal reduction to diagonal form, eigenvalues and geometric applications.

**MATH 350. Introductory Combinatorics. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisite: MATH 201 with a minimum grade of C. An introduction to basic combinatorial concepts such as combinations, permutations, binomial coefficients, Fibonacci numbers and Pascal's triangle; basic theorems such as the pigeonhole principle and Newton's binomial theorem; algorithms such as bubble sort and quicksort; and discussion of basic applications such as chessboard problems, combinatorial games, magic squares and Latin squares.

**MATH 351. Applied Abstract Algebra. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisite: MATH 300. A survey of several areas in applied abstract algebra which have applications in computer science such as groups, codes, matrix algebra, finite fields and advanced graph theory.

**MATH 353. Experimental Mathematics. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisite: MATH 201 with a minimum grade of C. An introduction to a mathematical computing package, computer manipulation of lists and sets, and symbolic computing. Numerical computation will be used to investigate mathematical objects, such as integers, prime numbers, graphs, matrices and to identify properties and patterns among these objects. Random methods will be used to explore properties and patterns in long sequences and large collections.

**MATH 356. Graphs and Algorithms. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisite: MATH 201 with a minimum grade of C. An introduction to basic graph theoretic concepts such as trees, colorings and matchings; basic theorems such as the handshaking lemma and the Gallai identities; algorithms such as Dijkstra's and Kruskal's; and discussion of famous open problems such as finding shortest tours for a traveling salesman.

**MATH 361. Numbers and Operations. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisite: TEDU 101 and either MATH 131 or satisfactory score on the VCU Mathematics Placement Test within the one-year period immediately preceding the beginning of the course. Ways of representing numbers, relationships between numbers, number systems, the meanings of operations and how they relate to one another, and computation within the number systems as a foundation for algebra. Structured observations and tutoring of elementary-level students. Restricted to students majoring in the liberal studies concentration for early and elementary education in the Bachelor of Interdisciplinary Studies program.

**MATH 362. Algebra and Functions. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisite: MATH 361. Topics include algebraic concepts, linear, quadratic, exponential, logarithmic, trigonometric functions including graphical modeling of physical phenomena. Attention will be given to the use of graphing technology, the transition from arithmetic to algebra, working with quantitative change, and the description and prediction of change. Structured observations and tutoring of elementary-level students. Restricted to B.I.S. students in the liberal studies for early and elementary education concentration.

**MATH 380. Introduction to Mathematical Biology. 4 Hours.**

Semester course; 3 lecture and 2 laboratory hours. 4 credits. Prerequisites: MATH 200 and BIOL 151, or permission of instructor. An introduction to mathematical biology. Various mathematical modeling tools will be covered and implemented in a range of biological areas. Additionally, the collaborative research process will be presented and discussed. Crosslisted as: BNFO 380/BIOL 380.

**MATH 391. Topics in Mathematics. 1-3 Hours.**

Semester course; 1-3 credits. May be repeated for credit. A study of selected topics in mathematics. See the Schedule of Classes for specific topics to be offered each semester and prerequisites.

**MATH 401. Introduction to Abstract Algebra. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisites: MATH 300 and MATH 310, each with a minimum grade of C. An introduction to groups, rings and fields from an axiomatic point of view. Coset decomposition and basic morphisms.

**MATH 404. Algebraic Structures and Functions. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisites: MATH 300 and MATH 310, each with a minimum grade of C; one additional mathematical sciences course; and permission of instructor. Semigroups, groups, rings, integral domains and fields. Exponential, logarithmic and trigonometric functions. Graphing in parametric and polar coordinates. Arithmetic and geometric sequences and series.

**MATH 407. Advanced Calculus. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisite: MATH 300. Theoretical aspects of calculus. Topics include properties of real numbers, countable and uncountable sets, sequences and series, limits, continuity, derivatives, and Riemann integration.

**MATH 409. General Topology. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisite: MATH 407 with a minimum grade of C. Foundations and fundamental concepts of point-set topology. Topological spaces, continuity, convergence, connected sets, compactness, product spaces, quotient spaces, function spaces, separation properties.

**MATH 415. Numerical Methods. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisites: MATH 255, MATH 301 and MATH 310, each with a minimum grade of C. Numerical methods for interpolation, solving systems of linear equations and initial value problems (ordinary differential equations) and the exploration of computational error.

**MATH 427. Excursions in Analysis: Real. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisites: MATH 307, MATH 310 and MATH 407. May be repeated once for credit with a different emphasis and permission of the instructor. Intensive study of ideas and applications from real analysis.

**MATH 428. Excursions in Analysis: Complex. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisites: MATH 307, MATH 310 and MATH 407. May be repeated once for credit with a different emphasis and permission of the instructor. Intensive study of ideas and applications from complex analysis.

**MATH 429. Excursions in Analysis: Applied. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisites: MATH 301, MATH 307, MATH 310 and MATH 407. May be repeated once for credit with a different emphasis and permission of the instructor. Intensive study of ideas and applications from applied analysis.

**MATH 430. The History of Mathematics. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisites: MATH 300, MATH 307, MATH 310, and either MATH 301 or OPER 327, all with a minimum grade of C. Surveys major trends in the development of mathematics from ancient times through the 19th century and considers the cultural and social contexts of mathematical activity.

**MATH 431. Expositions in Modern Mathematics. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisites: MATH 300, MATH 307, MATH 310, and either MATH 301 or OPER 327, all with a minimum grade of C. Descriptively studies several major ideas relevant to present-day mathematics, such as the advent of pure abstraction, difficulties in the logical foundations of mathematics, the impact of mathematics and statistics in the 20th century and the computer revolution.

**MATH 432. Ordinary Differential Equations. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisites: MATH 300, MATH 301, MATH 307 and MATH 310, each with a minimum grade of C. Existence and uniqueness of solutions, linearization and stability analysis, Lyapunov stability theory, periodic solutions, and bifurcations. Applications and simulations are emphasized.

**MATH 433. Partial Differential Equations. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisites: MATH 300, MATH 301, MATH 307 and MATH 310, each with a minimum grade of C. Parabolic (heat), hyperbolic (wave) and elliptic (steady-state) partial differential equations are studied. Solution techniques such as separation of variables, reflection methods, integral transform methods and numerical methods are demonstrated. Practical problems and applications are emphasized.

**MATH 434. Discrete Dynamical Systems. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisites: MATH 300, MATH 301, MATH 307 and MATH 310, each with a minimum grade of C. Theory and applications of difference equations including existence and uniqueness of solutions, linearization and stability, periodic solutions, and bifurcations.

**MATH 454. Using Technology in the Teaching of Mathematics. 3 Hours.**

Semester course; 2 lecture and 2 laboratory hours. 3 credits. Prerequisites: MATH 200 and STAT 212, each with a minimum grade of C; six additional credits in the mathematical sciences; and permission of the instructor. Using graphing calculators, calculator-based labs and computer software packages in teaching topics in algebra, geometry, trigonometry, statistics, finance and calculus.

**MATH 480. Methods of Applied Mathematics for the Life Sciences: Discrete. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisites: MATH 301, MATH 307, MATH 310 and MATH 380, each with a minimum grade of C. Focuses on the use of discrete dynamical system models to describe phenomena in biology and medicine. Students will explore the theoretical mathematics necessary to analyze these models. Computational solutions to these models will be developed and implemented to validate the models and to further explore the biological phenomena.

**MATH 481. Methods of Applied Mathematics for the Life Sciences: ODE. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisites: MATH 301, MATH 307, MATH 310 and MATH 380, each with a minimum grade of C. Focuses on the use of ordinary differential equation models to describe phenomena in biology and medicine. Students will explore the theoretical mathematics necessary to analyze these models. Computational solutions to these models will be developed and implemented to validate the models and to further explore the biological phenomena.

**MATH 482. Methods of Applied Mathematics for the Life Sciences: PDE. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisites: MATH 301, MATH 307, MATH 310 and MATH 380, each with a minimum grade of C. Focuses on the use of partial differential equation models to describe phenomena in biology and medicine. Students will explore the theoretical mathematics necessary to analyze these models. Computational solutions to these models will be developed and implemented to validate the model and to further explore the biological phenomena.

**MATH 490. Mathematical Expositions. 3 Hours.**

Semester course; 2 lecture hours. 2 credits. Prerequisites: UNIV 200 or HONR 200. Restricted to seniors in mathematical sciences with at least 85 credit hours taken toward the degree. Required for all majors in the Department of Mathematics and Applied Mathematics. A senior capstone course in the major designed to help students attain proficiency in expository mathematical writing and oral presentation, which require the efficient and effective use of mathematics and the English language. Students will learn a variety of topics in mathematics, write reviews of selected award-winning mathematics papers and write a senior paper.

**MATH 492. Independent Study. 1-4 Hours.**

Semester course; variable hours. 1-4 credits. Maximum 4 credits per semester; maximum total of 6 credits. Generally open only to students of junior or senior standing who have acquired at least 12 credits in the departmental discipline. Determination of the amount of credit and permission of instructor and department chair must be procured prior to registration for the course. The student must submit a proposal for investigating some area or problem not contained in the regular curriculum. The results of the student's study will be presented in a report.

**MATH 493. Mathematical Sciences Internship. 3 Hours.**

Semester course; the equivalent of at least 15 work hours per week for a 15-week semester. 3 credits. Mathematical sciences majors only with junior or senior standing. Admission by permission from the department chair. Through placement in a position in business, industry, government or the university, the student will serve as an intern in order to obtain a broader knowledge of the mathematical sciences and their applications.

**MATH 502. Abstract Algebra I. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisites: MATH 401 with a minimum grade of a C, or permission of instructor. A study of groups, subgroups, quotient groups and homomorphisms, group actions, sylow theorems, direct and semi-direct products, rings, integrals domains, and polynomial rings.

**MATH 505. Modern Geometry. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisites: MATH 300, and MATH 307 or MATH 310, or permission of instructor. Topics in Euclidean, projective and non-Euclidean geometries from a modern viewpoint.

**MATH 507. Bridge to Modern Analysis. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Enrollment restricted to student with graduate standing. Metric spaces, normed vector spaces, inner-product spaces and orthogonality, sequences and series of functions, convergence, compactness, completeness, continuity, contraction mapping theorem, and inverse and implicit function theorems.

**MATH 511. Applied Linear Algebra. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisite: MATH 310 or permission of instructor. The algebra of matrices, the theory of finite dimensional vector spaces and the basic results concerning eigenvectors and eigenvalues, with particular attention to applications.

**MATH 515. Numerical Analysis. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Enrollment restricted to student with graduate standing. Knowledge of a programming language or mathematical software package recommended. Theoretical derivation and implementation of numerical methods. Topics to include direct methods, data fitting, differentiation, integration and solutions to ordinary differential equations.

**MATH 535. Introduction to Dynamical Systems. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Enrollment restricted to students with graduate standing. Theoretical and computational introduction to continuous and discrete dynamical systems with applications. Topics include existence and uniqueness of solutions, stability and bifurcations.

**MATH 550. Combinatorics. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisites: MATH 211 or MATH 300; and MATH 350, both with a minimum grade of C; or permission of instructor. Topics include basic counting, binomial theorems, combinations and permutations, recurrence relations, generating functions, and basic graph theory with emphasis to applications.

**MATH 555. Dynamics and Multivariable Control I. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisite: MATH 301 and 310 or the equivalent. Systems of differential equations with controls, linear control systems, controllability, observability, introduction to feedback control and stabilization. Crosslisted as: EGRE 555.

**MATH 556. Graph Theory. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisites: MATH 211 or MATH 300; MATH 310; and MATH 356, each with a minimum grade of C; or permission of instructor. Introduction to graph classes, graph invariants, graph algorithms, graph theoretic proof techniques and applications.

**MATH 585. Biomathematics Seminar: \_\_\_\_\_. 1 Hour.**

Semester course; 2 lecture hours. 1 credit. Prerequisite: MATH 301 or permission of instructor. May be repeated with different thematic content. Opportunity for students to develop their understanding of the connection between mathematics and the areas of biology and medicine. Activities include reading of classical and contemporary research literature, attending seminar talks and class discussions.

**MATH 591. Topics in Mathematics. 1-3 Hours.**

Semester course; 1-3 credits. May be repeated for credit with different topics. Prerequisite: permission of the instructor. Open to qualified undergraduates. A study of selected topics in mathematical sciences. See the Schedule of Classes for specific topics to be offered each semester and prerequisites.

**MATH 593. Internship in Mathematical Sciences. 3,6 Hours.**

Semester course; variable hours. 1-6 credits. May be repeated for credit. Student participation in a planned educational experience under the supervision of a mathematical sciences faculty member. The internship may include supervised teaching, statistical consulting or participation in theoretical or applied research projects. A grade of P may be assigned students in this course. May be applied toward the degree in mathematical sciences only with the permission of the graduate affairs committee.

**MATH 602. Abstract Algebra II. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisite: MATH 502. A study of modules, vector spaces, field extensions and Galois theory.

**MATH 607. Measure and Integration Theory. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisite: Math 507. Measurable sets and functions, sets of measure zero, Borel sets, Lebesgue measure and integral, fundamental convergence theorems,  $L_p$  spaces, and foundations of probability theory.

**MATH 610. Advanced Linear Algebra. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Vector spaces, bases and dimension, change of basis. Linear transformations, linear functionals. Simultaneous triangularization and diagonalization. Rational and Jordan canonical forms.

**MATH 615. Iterative Numerical Methods. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisite: MATH 515. Theoretical development of solutions to large linear and nonlinear systems by iterative methods with consideration given to optimal implementation.

**MATH 632. Ordinary Differential Equations I. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisites: MATH 507 and MATH 535. Linear systems theory; existence, uniqueness and continuous dependence for nonlinear systems; invariant manifolds; stable manifold theorem; Hartman-Grobman theorem; Lyapunov stability theory; Hamiltonian and gradient systems.

**MATH 633. Partial Differential Equations. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisite: MATH 507. Classification of partial differential equations, initial and boundary value problems, well-posedness; first-order equations and methods of characteristics; wave equation; heat equation, transform methods, maximum principle, energy methods; Laplace's equation. Other topics may vary depending on the interest of the students and the instructor.

**MATH 640. Mathematical Biology I. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisite: MATH 535. Mathematical modeling in the biological and medical sciences. Topics will include continuous and discrete dynamical systems describing interacting and structured populations, resource management, biological control, reaction kinetics, biological oscillators and switches, and the dynamics of infectious diseases.

**MATH 650. Advanced Combinatorics. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisite: MATH 550. Topics include advanced applications of the pigeonhole principle and inclusion-exclusion principle, recurrence relations, generating functions, special counting sequences, Ramsey theory, and combinatorial designs and codes.

**MATH 655. Dynamics and Multivariable Control II. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisites: MATH 555 and MATH 507 recommended, or permission of instructor. Control problems for nonlinear systems of ordinary differential equations, methods of feedback control to achieve control objectives. Crosslisted as: ENGR 655.

**MATH 656. Advanced Graph Theory. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisite: MATH 556. This course lays a rigorous theoretical foundation for further advanced study in graph theory. Topics may include connectivity, matching, planarity, coloring, Hamiltonian cycles and topological graph theory, as well as further advanced material.

**MATH 661. Number and Operations. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Ways of representing numbers, relationships between numbers, number systems, the meanings of operations and how they relate to one another, and computation within the number system as a foundation for algebra; episodes in history and development of the number system; and examination of the developmental sequence and learning trajectory as children learn number concepts. A core course for preparation as a K-8 mathematics specialist. Not applicable to M.S. in Mathematical Sciences.

**MATH 662. Geometry and Measurement. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Explorations of the foundations of informal measurement and geometry in one, two and three dimensions. The van Hiele model for geometric learning is used as a framework for how children build their understanding of length, area, volume, angles and geometric relationships. Visualization, spatial reasoning and geometric modeling are stressed. As appropriate, transformational geometry, congruence, similarity and geometric constructions will be discussed. A core course of preparation as a K-8 mathematics specialist. Not applicable to M.S. in Mathematical Sciences.

**MATH 663. Functions and Algebra. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Examination of representation and analysis of mathematical situations and structures using generalization and algebraic symbols and reasoning. Attention will be given to the transition from arithmetic to algebra, working with quantitative change, and the description of and prediction of change. A core course for preparation as a K-8 mathematics specialist. Not applicable to M.S. in Mathematical Sciences.

**MATH 664. Statistics and Probability. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. An introduction to probability, descriptive statistics and data analysis; exploration of randomness, data representation and modeling. Descriptive statistics will include measures of central tendency, dispersion, distributions and regression. Analysis of experiments requiring hypothesizing, experimental design and data gathering. A core course for preparation as a K-8 mathematics specialist. Not applicable to M.S. in Mathematical Sciences.

**MATH 665. Rational Numbers and Proportional Reasoning. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Basic number strands in fractions and rational numbers, decimals and percents; ratios and proportions in the school curriculum. Interpretations, computations and estimation with a coordinated program of activities that develop both rational number concepts and skills and proportional reasoning. A core course for preparation as a K-8 mathematics specialist. Not applicable to M.S. in Mathematical Sciences.

**MATH 667. Functions and Algebra II. 3 Hours.**

Semester course; 3 lecture hours, 3 credits. Prerequisite: Math 663 or equivalent. Examination of the K-8 strands related to algebra. A study of linear, exponential and quadratic functions. Use of number lines, coordinate axes, tables, graphing calculators and manipulatives to understand core algebraic ideas and real-world contexts. Course provides preparation for K-8 mathematics specialists. Not applicable to M.S. in Mathematical Sciences.

**MATH 690. Research Seminar. 2 Hours.**

Semester course; 2 lecture hours; 2 credits. Enrollment is restricted to students with graduate standing. Discussion of topics in the mathematical sciences stimulated by independent reading in selected area. Each student will give at least one oral presentation and complete an expository writing assignment.

**MATH 691. Special Topics in Mathematics. 1-3 Hours.**

Semester course; 1-3 lecture hours. 1-3 credits. May be repeated for credit. Prerequisite: permission of instructor. A detailed study of selected topics in mathematics. Possible topics include commutative rings and algebras, topological groups, special functions, Fourier analysis, abstract harmonic analysis, operator theory, functional analysis, differential geometry, Banach algebras and control theory.

**MATH 697. Directed Research. 1-3 Hours.**

Semester course; variable hours. 1-3 credits per semester. May be repeated for credit. Prerequisite: graduate standing. Supervised individual research and study in an area not covered in the present curriculum or in one which significantly extends present coverage. Research culminates with an oral presentation and submission of a written version of this presentation to the supervising faculty member.

**MATH 698. Thesis. 1-3 Hours.**

Hours to be arranged. 1-3 credits. A total of 3 or 6 credits may be applied to the M.S. in Mathematical Sciences/Applied Mathematics or to the M.S. in Mathematical Sciences/Mathematics. May be repeated for credit. Prerequisite: graduate standing. Independent research culminating in the writing of the required thesis as described in this bulletin. Grade of S/U/F may be assigned in this course.

**MATH 707. Functional Analysis I. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisite: MATH 507. Banach and Hilbert spaces, bounded linear maps, Hahn-Banach theorem, open mapping theorem, dual spaces, weak topologies, Banach-Alaoglu theorem, reflexive spaces, compact operators, spectral theory in Hilbert spaces.

**MATH 715. Numerical Solutions for Differential Equations. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisite: MATH 515 or MATH 615. Students will use the finite difference method and the finite element method to solve ordinary and partial differential equations. Course will explore the theoretical underpinnings of the techniques and implement the methods to solve a variety of equations.

**MATH 727. Topics in Analysis: \_\_\_\_\_. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. May be repeated for credit with different topics. A detailed study of selected topics, which may include complex analysis, geometric analysis, harmonic analysis, mathematical logic, nonlinear functional analysis, nonstandard analysis and variational analysis.

**MATH 732. Ordinary Differential Equations II. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. Prerequisite: MATH 632. Center manifold theory; normal form theory; oscillations in nonlinear systems; local bifurcation theory of equilibria and periodic orbits.

**MATH 750. Topics in Combinatorics: \_\_\_\_\_. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. May be repeated with different topics for credit. Prerequisite: MATH 650. A detailed study of selected topics, which may include probabilistic methods, linear algebra methods, extremal problems, partially ordered sets and symmetric functions.

**MATH 756. Topics in Graph Theory: \_\_\_\_\_. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. May be repeated with different topics for credit. Prerequisite: MATH 656. A detailed study of selected topics, which may include extremal graph theory, spectral graph theory, infinite graphs, random graphs and graph minors.

**MATH 769. Topics in Applied Mathematics: \_\_\_\_\_. 3 Hours.**

Semester course; 3 lecture hours. 3 credits. May be repeated with different topics for credit. A detailed study of selected topics, which may include advanced partial differential equations, discrete dynamical systems, fluid dynamics, computational physiology, disease dynamics, kinetic theory, optimal transportation, numerical optimization and population dynamics.