

MATHEMATICS

math.northwestern.edu

Mathematics, often celebrated as the “Queen of the Sciences,” has long been an indispensable tool in the physical sciences, engineering, and commerce. Today the social sciences and humanities also use mathematics in increasingly sophisticated ways. Students majoring or minoring in mathematics have an opportunity to learn about its diverse applications, as well as to acquire an understanding of both the foundations and the frontiers of the discipline.

The department offers a major and a minor in mathematics. The mathematics major is flexible, accommodating students interested in the foundations of the modern mathematical sciences, those primarily interested in applications to the natural or social sciences, and those interested in management or engineering.

Students with sufficiently strong preparation who seek an early exposure to rigorous mathematics should consider participating in Mathematical Experience for Northwestern Undergraduates (MENU) - see “Course Recommendations” below for more information. The department also encourages appropriately prepared undergraduate students to enroll in its graduate courses.

Course Recommendations

First-Year Placement

For information regarding course placement for first-year students, see our First Year Focus (<http://www.math.northwestern.edu/undergraduate/first-year-focus>).

Mathematical Experience for Northwestern Undergraduates (MENU)

Mathematical Experience for Northwestern Undergraduates (MENU) (<http://math.northwestern.edu/undergraduate/menu>) is a flexible program of challenging courses designed to provide qualified undergraduates with a thorough foundation in mathematics suitable for advanced study in mathematics and its applications across a wide range of disciplines.

MENU offers students an opportunity to expand their mathematical knowledge while retaining flexibility about their majors. Although MENU attracts participants with a variety of interests, the program is especially well-suited for students considering a major in mathematics, the natural sciences, or economics. The director of MENU is available to advise all MENU participants regardless of major.

During the first year MENU participants typically enroll in one of two yearlong sequences:

Course	Title
MATH 290-1 & MATH 290-2 & MATH 290-3 or MATH 291-1 & MATH 291-2 & MATH 291-3	MENU: Linear Algebra and Multivariable Calculus and MENU: Linear Algebra and Multivariable Calculus and MENU: Linear Algebra and Multivariable Calculus MENU: Intensive Linear Algebra and Multivariable Calculus and MENU: Intensive Linear Algebra and Multivariable Calculus and MENU: Intensive Linear Algebra and Multivariable Calculus

Each sequence provides a strong background in linear algebra and multivariable calculus. In contrast to our standard mathematics courses, these sequences develop linear algebra before multivariable calculus and use linear algebra as an important tool in the study of multivariable calculus. In particular, MATH 291-1 emphasizes theory and proofs and is appropriate for students who are particularly skilled in and passionate about mathematics. Students may transfer between MATH 290-1 and MATH 291-1 with permission from the director of MENU.

After the first year MENU participants may choose among four upper-level MENU sequences:

Course	Title
MATH 311-1 & MATH 311-2 & MATH 311-3	MENU: Probability and Stochastic Processes and MENU: Probability and Stochastic Processes and MENU: Probability and Stochastic Processes
MATH 321-1 & MATH 321-2 & MATH 321-3	MENU: Real Analysis and MENU: Real Analysis and MENU: Real Analysis
MATH 331-1 & MATH 331-2 & MATH 331-3	MENU: Abstract Algebra and MENU: Abstract Algebra and MENU: Abstract Algebra
MATH 360-1 & MATH 360-2	MENU: Applied Analysis and MENU: Applied Analysis

or they may enroll in other advanced mathematics courses.

Participation in MENU is by invitation only. Students who earn a score of at least 4 on the Advanced Placement Calculus BC examination should automatically receive an invitation to participate. A student who does not automatically receive an invitation can obtain one from the director of MENU if he or she is

- an international student who has completed single variable calculus, or
- has completed a college-level sequence in single variable calculus with high grades, or
- has earned a score of 7 on the International Baccalaureate Higher-Level Mathematics Examination.

Students who excel in MATH 220-0 and MATH 224-0 may consult the director of MENU about continuing their studies of mathematics in MENU. Further information is available at math.northwestern.edu/undergraduate/menu.

Mathematics and Economics

Students interested in mathematics and economics should consider the following course sequences:

Course	Title
MATH 320-1 & MATH 320-2 & MATH 320-3 or MATH 321-1 & MATH 321-2 & MATH 321-3	Real Analysis and Real Analysis and Real Analysis MENU: Real Analysis and MENU: Real Analysis and MENU: Real Analysis
MATH 310-1 & MATH 310-2 & MATH 310-3 or MATH 311-1 & MATH 311-2 & MATH 311-3	Probability and Stochastic Processes and Probability and Stochastic Processes and Probability and Stochastic Processes MENU: Probability and Stochastic Processes and MENU: Probability and Stochastic Processes and MENU: Probability and Stochastic Processes

ECON 380-1 & ECON 380-2	Game Theory and Game Theory
ECON 381-1 & ECON 381-2	Econometrics and Econometrics

Actuarial Science

Students interested in actuarial science should consider the following courses and course sequences:

Course	Title
MATH 310-1 & MATH 310-2 & MATH 310-3 or MATH 311-1 & MATH 311-2 & MATH 311-3	Probability and Stochastic Processes and Probability and Stochastic Processes and Probability and Stochastic Processes MENU: Probability and Stochastic Processes and MENU: Probability and Stochastic Processes and MENU: Probability and Stochastic Processes
MATH 320-1 & MATH 320-2 & MATH 320-3 or MATH 321-1 & MATH 321-2 & MATH 321-3	Real Analysis and Real Analysis and Real Analysis MENU: Real Analysis and MENU: Real Analysis and MENU: Real Analysis
STAT 320-2 & STAT 320-3	Statistical Methods 2 and Statistical Methods 3
STAT 350-0	Regression Analysis
STAT 351-0	Design and Analysis of Experiments
STAT 352-0	Nonparametric Statistical Methods
STAT 355-0	Analysis of Qualitative Data

Programs of Study

- Mathematics Major (<https://catalogs.northwestern.edu/undergraduate/arts-sciences/mathematics/mathematics-major>)
- Mathematics Minor (<https://catalogs.northwestern.edu/undergraduate/arts-sciences/mathematics/mathematics-minor>)
- Mathematics Second Major for ISP Students (<https://catalogs.northwestern.edu/undergraduate/arts-sciences/mathematics/mathematics-second-major-isp-students>)
- Mathematics Second Major or Minor for MMSS Students (<https://catalogs.northwestern.edu/undergraduate/arts-sciences/mathematics/mathematics-second-major-minor-mmss-students>)

The director of undergraduate studies may waive prerequisites for mathematics courses. However, without the permission of the department, no waived prerequisite course is eligible for credit after a student completes another course for which it is prerequisite. Except for MATH 100-0 Quantitative Reasoning and MATH 105-6 First-Year Seminar, no 100 level course may be taken for credit after completing a 200 or higher-level course. See the course descriptions for other restrictions. See Weinberg College Policies (<https://catalogs.northwestern.edu/undergraduate/arts-sciences/#academicpolicies>) for additional information about mathematics courses and distribution requirements.

MATH 100-0 Quantitative Reasoning (1 Unit) Analyzing topical, real-life problems from a quantitative perspective. Developing facility with basic algebra, probability, and statistics to solve multistep problems. *Formal Studies Distro Area*

MATH 100-BR Quantitative Reasoning (1 Unit) For participants in Bridge I summer program. Analyzing topical, real-life problems from a quantitative perspective. Developing facility with basic algebra,

probability, and statistics to solve multistep problems. Taken with either CHEM 100-BR or ECON 100-BR.

MATH 104-0 Introduction to Game Theory (1 Unit) Introduction to the mathematical theory of strategic competition. Optimal strategies and equilibria. The prisoner's dilemma. Bargaining and negotiation. Strategic voting. Applications to economics and political science. For students with minimal mathematical background. *Formal Studies Distro Area*

MATH 105-6 First-Year Seminar (1 Unit) Topics vary. *WCAS First-Year Seminar*

MATH 110-0 Introduction to Mathematics (1 Unit) Exploration of the beauty of mathematics through a study of the patterns and properties of the natural numbers. Topics include counting, probability, prime numbers, the Euclidean algorithm, and unique factorization. For students with minimal mathematical background. *Formal Studies Distro Area*

MATH 202-0 Finite Mathematics (1 Unit) Topics chosen from elementary linear algebra and its applications, finite probability, and elementary statistics. For students majoring in the behavioral sciences. *Formal Studies Distro Area*

MATH 211-0 Short Course in Calculus (1 Unit) Elements of differential and integral calculus. Students may not receive credit for both MATH 211-0 and any of MATH 212-0, MATH 213-0, MATH 220-0, or MATH 224-0. Not suitable for students planning to major in mathematics, the natural sciences, or economics. *Formal Studies Distro Area*

MATH 212-0 Single Variable Calculus I (1 Unit) Review of functions and graphs. Limits, differentiation, related rates, linear approximation, l'Hopital's rule, and transcendental functions. For students with little or no previous exposure to calculus who are not confident about their mathematical preparation. Students may not receive credit for both MATH 212-0 and either MATH 211-0 or MATH 220-0. Prerequisite: consent of the department. *Formal Studies Distro Area*

MATH 213-0 Single Variable Calculus II (1 Unit) Optimization and curve sketching. Antiderivatives. Integration and techniques of integration. Students may not receive credit for both MATH 213-0 and MATH 211-0. Prerequisite: MATH 212-0 or consent of the department. *Formal Studies Distro Area*

MATH 214-0 Single Variable Calculus III (1 Unit) Improper integrals, areas and volumes, sequences and series, and Taylor polynomials. Students may not receive credit for both MATH 214-0 and MATH 224-0. Prerequisite: MATH 213-0 or consent of the department. *Formal Studies Distro Area*

MATH 220-0 Differential Calculus of One-Variable Functions (1 Unit) Limits, differentiation, related rates, linear approximation, optimization, curve sketching, Newton's method, and antiderivatives. Students may not receive credit for both MATH 220-0 and either MATH 211-0 or MATH 212-0. *Formal Studies Distro Area*

MATH 224-0 Integral Calculus of One-Variable Functions (1 Unit) Integration, techniques of integration, areas and volumes, sequences and series, and Taylor polynomials. Students may not receive credit for both MATH 224-0 and either of MATH 211-0 or MATH 214-0. Prerequisite: MATH 220-0 or consent of the department. *Formal Studies Distro Area*

MATH 230-0 Differential Calculus of Multivariable Functions (1 Unit) Vectors, vector functions, partial derivatives, and optimization. Students may not receive credit for both MATH 230-0 and any of MATH 281-1,

MATH 285-2, MATH 290-2, MATH 291-2, or ES_APPM 252-1. Prerequisite: MATH 214-0 or MATH 224-0. *Formal Studies Distro Area*

MATH 234-0 Multiple Integration and Vector Calculus (1 Unit)

Multiple integration: double integrals, triple integrals, and the change of variables theorem. Vector calculus: vector fields, line integrals, surface integrals, curl and divergence, Green's theorem, Stokes' theorem, and the divergence theorem. Students may not receive credit for both MATH 234-0 and any of MATH 281-2, MATH 285-3, MATH 290-3, MATH 291-3, or ES_APPM 252-2. Prerequisite: MATH 230-0 or MATH 281-1 or MATH 285-2 or MATH 290-2 or MATH 291-2 or ES_APPM 252-1. *Formal Studies Distro Area*

MATH 240-0 Linear Algebra (1 Unit) Elementary linear algebra: systems of linear equations, matrix algebra, subspaces, determinants, eigenvalues, eigenvectors, and orthogonality. Students may not receive credit for both MATH 240-0 and any of MATH 281-3, MATH 285-1, MATH 290-1, MATH 291-1, GEN_ENG 205-1, or GEN_ENG 206-1. Prerequisite: MATH 230-0 or MATH 281-1 or ES_APPM 252-1. *Formal Studies Distro Area*

MATH 250-0 Elementary Differential Equations (1 Unit) Elementary ordinary differential equations: first-order equations, second-order linear equations, series solutions, and systems of first-order linear equations. Students may not receive credit for both MATH 250-0 and any of MATH 281-3, MATH 360-1, GEN_ENG 205-4, or GEN_ENG 206-4. Prerequisites: MATH 234-0 or MATH 281-2 or MATH 285-3 or MATH 290-3 or MATH 291-3 or ES_APPM 252-2; and MATH 240-0 or MATH 285-1 or MATH 290-1 or MATH 291-1 or GEN_ENG 205-1 or GEN_ENG 206-1. *Formal Studies Distro Area*

MATH 281-1 Accelerated Mathematics for ISP: First Year (1 Unit)

Multivariable differential and integral calculus. Students may not receive credit for both MATH 281-1 and any of MATH 230-0, MATH 285-2, MATH 290-2, MATH 291-2, or ES_APPM 252-1. Prerequisite: first-year standing in ISP. *Formal Studies Distro Area*

MATH 281-2 Accelerated Mathematics for ISP: First Year (1 Unit) Vector calculus, ordinary differential equations, and infinite series. Students may not receive credit for both MATH 281-2 and any of MATH 234-0, MATH 285-3, MATH 290-3, MATH 291-3, or ES_APPM 252-2. Prerequisite: MATH 281-1. *Formal Studies Distro Area*

MATH 281-3 Accelerated Mathematics for ISP: First Year (1 Unit) Linear algebra and systems of ordinary differential equations. Students may not receive credit for both MATH 281-3 and any of MATH 240-0, MATH 250-0, MATH 285-1, MATH 290-1, MATH 291-1, MATH 360-1, GEN_ENG 205-1, GEN_ENG 206-1, GEN_ENG 205-4, or GEN_ENG 206-4. Prerequisite: MATH 281-2. *Formal Studies Distro Area*

MATH 285-1 Accelerated Mathematics for MMSS: First Year (1 Unit)

Linear algebra: systems of linear equations, linear transformations, determinants, vector spaces, eigenvalues and eigenvectors. Students may not receive credit for both MATH 285-1 and any of MATH 240-0, MATH 281-3, MATH 290-1, MATH 291-1, GEN_ENG 205-1, or GEN_ENG 206-1. Prerequisite: first-year standing in MMSS. *Formal Studies Distro Area*

MATH 285-2 Accelerated Mathematics for MMSS: First Year (1 Unit)

Linear algebra: orthogonality, symmetric matrices, and quadratic forms. Multivariable differential calculus: vectors, differentiation, vector-valued functions, and optimization. Students may not receive credit for both MATH 285-2 and any of MATH 230-0, MATH 281-1, MATH 290-2,

MATH 291-2, or ES_APPM 252-1. Prerequisite: MATH 285-1. *Formal Studies Distro Area*

MATH 285-3 Accelerated Mathematics for MMSS: First Year (1 Unit)

Multivariable integral calculus: multiple integration, line integrals, surface integrals, and vector analysis. Students may not receive credit for both MATH 285-3 and any of MATH 234-0, MATH 281-2, MATH 290-3, MATH 291-3, or ES_APPM 252-2. Prerequisite: MATH 285-2. *Formal Studies Distro Area*

MATH 290-1 MENU: Linear Algebra and Multivariable Calculus (1 Unit)

Linear algebra: systems of linear equations, linear transformations, determinants, eigenvalues and eigenvectors. Students may not receive credit for both MATH 290-1 and any of MATH 240-0, MATH 281-3, MATH 285-1, MATH 291-1, GEN_ENG 205-1, or GEN_ENG 206-1. Prerequisite: consent of the department. *Formal Studies Distro Area*

MATH 290-2 MENU: Linear Algebra and Multivariable Calculus (1 Unit)

Linear algebra: orthogonality, symmetric matrices, and quadratic forms. Multivariable differential calculus: vectors, differentiation, vector-valued functions, and optimization. Students may not receive credit for both MATH 290-2 and any of MATH 230-0, MATH 281-1, MATH 285-2, MATH 291-2, or ES_APPM 252-1. Prerequisite: MATH 290-1. *Formal Studies Distro Area*

MATH 290-3 MENU: Linear Algebra and Multivariable Calculus (1 Unit)

Multivariable integral calculus: multiple integration, line integrals, surface integrals, and vector analysis. Students may not receive credit for both MATH 290-3 and any of MATH 234-0, MATH 281-2, MATH 285-3, MATH 291-3, or ES_APPM 252-2. Prerequisite: MATH 290-2. *Formal Studies Distro Area*

MATH 291-1 MENU: Intensive Linear Algebra and Multivariable Calculus (1 Unit)

Foundations. Linear algebra: systems of linear equations, linear transformations, subspaces, vector spaces, and determinants. The course emphasizes theory and proofs. Students may not receive credit for both MATH 291-1 and any of MATH 240-0, MATH 281-3, MATH 285-1, MATH 290-1, GEN_ENG 205-1, or GEN_ENG 206-1. Prerequisite: consent of the department. *Formal Studies Distro Area*

MATH 291-2 MENU: Intensive Linear Algebra and Multivariable Calculus (1 Unit)

Linear algebra: eigenvalues and eigenvectors, orthogonality, symmetric matrices, and quadratic forms. Multivariable differential calculus: vectors, differentiation, and vector-valued functions. The course emphasizes theory and proofs. Students may not receive credit for both MATH 291-2 and any of MATH 230-0, MATH 281-1, MATH 285-2, MATH 290-2, or ES_APPM 252-1. Prerequisite: MATH 291-1 or consent of the department. *Formal Studies Distro Area*

MATH 291-3 MENU: Intensive Linear Algebra and Multivariable Calculus (1 Unit)

Multivariable differential calculus: optimization. Multivariable integral calculus: multiple integration, line integrals, surface integrals, and vector analysis. The course emphasizes theory and proofs. Students may not receive credit for both MATH 291-3 and any of MATH 234-0, MATH 281-2, MATH 285-3, MATH 290-3, or ES_APPM 252-2. Prerequisite: MATH 291-2 or consent of the department. *Formal Studies Distro Area*

MATH 300-0 Foundations of Higher Mathematics (1 Unit) Introduction to fundamental mathematical structures, including sets, functions, equivalence relations, and cardinal numbers. Elementary logic and proof techniques. Without prior departmental consent students may not receive credit for MATH 300-0 after passing any of MATH 320-1, MATH 321-1, MATH 330-1, or MATH 331-1. Prerequisite: MATH 240-0 or MATH 281-3

or MATH 285-1 or MATH 290-1 or MATH 291-1 or GEN_ENG 205-1 or GEN_ENG 206-1 or consent of the department. *Formal Studies Distro Area*

MATH 306-0 Combinatorics & Discrete Mathematics (1 Unit) Discrete mathematics, inductive reasoning, counting problems, binomial coefficients and Pascal's triangle, Fibonacci numbers, combinatorial probability, divisibility and primes, partitions, and generating functions. Prerequisite: MATH 240-0 or MATH 281-3 or MATH 285-1 or MATH 290-1 or MATH 291-1 or GEN_ENG 205-1 or GEN_ENG 206-1 or consent of the instructor. *Formal Studies Distro Area*

MATH 308-0 Graph Theory (1 Unit) Introduction to graph theory: graphs, trees, matchings, planar graphs, and colorings. Additional topics as time permits. Prerequisite: MATH 291-1 or MATH 300-0 or MATH 306-0. *Formal Studies Distro Area*

MATH 310-1 Probability and Stochastic Processes (1 Unit) Axioms of probability. Conditional probability and independence. Random variables. Joint distributions. Expectation. Limit theorems: the weak law of large numbers and the central limit theorem. Students may not receive credit for both MATH 310-1 and any of MATH 311-1, MATH 314-0, MATH 385-0, STAT 320-1, STAT 383-0, IEMS 202-0, or EECS 302-0. Prerequisite or Corequisite: MATH 234-0 or MATH 281-2 or MATH 285-3 or MATH 290-3 or MATH 291-3 or ES_APPM 252-2. *Formal Studies Distro Area*

MATH 310-2 Probability and Stochastic Processes (1 Unit) Discrete-time Markov chains, recurrence and transience. Students may not receive credit for both MATH 310-2 and MATH 311-2. Prerequisites: MATH 240-0 or MATH 281-3 or MATH 285-1 or MATH 290-1 or MATH 291-1 or GEN_ENG 205-1 or GEN_ENG 206-1; and MATH 310-1 or MATH 311-1. *Formal Studies Distro Area*

MATH 310-3 Probability and Stochastic Processes (1 Unit) Continuous-time Markov chains, queues, population growth models. Brownian motion and other diffusion processes. Additional topics as time permits. Students may not receive credit for both MATH 310-3 and MATH 311-3. Prerequisite: MATH 310-2 or MATH 311-2. *Formal Studies Distro Area*

MATH 311-1 MENU: Probability and Stochastic Processes (1 Unit) Probability spaces. Random variables. Independence. Distributions. Generating functions. The central limit theorem. Students may not receive credit for both MATH 311-1 and any of MATH 310-1, MATH 314-0, MATH 385-0, STAT 320-1, STAT 383-0, IEMS 202-0, or EECS 302-0. Recommended: MATH 320-1 or MATH 321-1. Prerequisite: MATH 291-3; or MATH 300-0 and MATH 290-3, MATH 281-2, MATH 285-3 or ES_APPM 252-2; or consent of the department. *Formal Studies Distro Area*

MATH 311-2 MENU: Probability and Stochastic Processes (1 Unit) Markov chains, convergence of random variables, random processes, renewals, and queues. Students may not receive credit for both MATH 311-2 and MATH 310-2. Prerequisite: MATH 311-1 or consent of the department. *Formal Studies Distro Area*

MATH 311-3 MENU: Probability and Stochastic Processes (1 Unit) Stationary processes, martingales, and diffusion processes. Students may not receive credit for both MATH 311-3 and MATH 310-3. Prerequisite: MATH 311-2 or consent of the department. *Formal Studies Distro Area*

MATH 314-0 Probability and Statistics for Econometrics (1 Unit) Introduction to probability theory and statistical methods, including properties of probability distributions, sampling distributions, estimation, confidence intervals and hypothesis testing. For students planning to take ECON 381-1. Students may not receive credit for both MATH 314-0

and any of MATH 310-1, MATH 311-1, MATH 385-0, STAT 320-1, STAT 383-0, IEMS 202-0, or EECS 302-0. Prerequisite or Corequisite: MATH 234-0 or MATH 281-1 or MATH 285-3 or MATH 290-3 or MATH 291-3. *Formal Studies Distro Area*

MATH 320-1 Real Analysis (1 Unit) Analysis on the real line: axiomatic development of the real number system, sequences and series of real numbers, continuity, and differentiability. Students may not receive credit for both MATH 320-1 and MATH 321-1. Prerequisite: MATH 300-0 or MATH 291-3 or consent of the department. *Formal Studies Distro Area*

MATH 320-2 Real Analysis (1 Unit) Analysis on the real line: the Riemann integral and sequences and series of functions. Additional topics as time permits. Students may not receive credit for both MATH 320-2 and MATH 321-2. Prerequisite: MATH 320-1 or MATH 321-1. *Formal Studies Distro Area*

MATH 320-3 Real Analysis (1 Unit) Analysis on Euclidean spaces: the topology of Euclidean spaces, limits, continuity, and differentiability, including the inverse and implicit function theorems. Additional topics as time permits. Students may not receive credit for both MATH 320-3 and MATH 321-2. Prerequisite: MATH 320-2. *Formal Studies Distro Area*

MATH 321-1 MENU: Real Analysis (1 Unit) Analysis on metric spaces: the real number system, the topology of metric spaces, sequences and series, continuity, and differentiability. Students may not receive credit for both MATH 321-1 and MATH 320-1. Prerequisite: MATH 291-3; or MATH 300-0 and consent of the department. *Formal Studies Distro Area*

MATH 321-2 MENU: Real Analysis (1 Unit) Analysis on metric spaces: the Riemann integral, sequences and series of functions, and functions of several variables, including the inverse and implicit function theorems. Students may not receive credit for both MATH 321-2 and either MATH 320-2 or MATH 320-3. Prerequisite: MATH 321-1. *Formal Studies Distro Area*

MATH 321-3 MENU: Real Analysis (1 Unit) Lebesgue measure and the Lebesgue integral. Additional topics as time permits. Prerequisite: MATH 321-2. *Formal Studies Distro Area*

MATH 325-0 Complex Analysis (1 Unit) Complex numbers. Analytic functions. Cauchy's theorem and the Cauchy integral formula. Series. Residues. Conformal mapping. Students may not receive credit for both MATH 325-0 and ES_APPM 312-0. Prerequisites: MATH 234-0 and MATH 240-0; or MATH 281-3 or MATH 285-3 or MATH 290-3 or MATH 291-3 or ES_APPM 252-2. *Formal Studies Distro Area*

MATH 327-0 Mechanics for Mathematicians (1 Unit) Fundamental mathematical ideas arising in classical mechanics: Newtonian mechanics, Lagrangian formalism and the calculus of variations, motion with constraints, symmetries and conservation laws, and Hamiltonian mechanics, and Liouville's theorem. No prior knowledge of physics required. Students may not receive credit for MATH 327-0 after taking PHYSICS 330-1. Prerequisites: MATH 234-0 and MATH 240-0; or MATH 281-3 or MATH 285-3 or MATH 290-3 or MATH 291-3 or ES_APPM 252-2. *Formal Studies Distro Area Interdisciplinary Distro - See Rules* (<https://catalogs.northwestern.edu/undergraduate/arts-sciences/#schoolrequirementstext>) *Natural Sciences Distro Area*

MATH 330-1 Abstract Algebra (1 Unit) Group theory. Students may not receive credit for both MATH 330-1 and MATH 331-1. Prerequisite: MATH 291-1 or MATH 300-0. *Formal Studies Distro Area*

MATH 330-2 Abstract Algebra (1 Unit) Ring theory, including polynomial rings. Students may not receive credit for both MATH 330-2 and MATH 331-2. Prerequisite: MATH 330-1 or MATH 331-1 or consent of the instructor. *Formal Studies Distro Area*

MATH 330-3 Abstract Algebra (1 Unit) Field theory and Galois theory. Students may not receive credit for both MATH 330-3 and MATH 331-3. Prerequisite: MATH 330-2 or MATH 331-2 or consent of the instructor. *Formal Studies Distro Area*

MATH 331-1 MENU: Abstract Algebra (1 Unit) Group theory, including the Sylow theorems. Students may not receive credit for both MATH 331-1 and MATH 330-1. Prerequisite: MATH 291-3; or MATH 300-0 and consent of the department. *Formal Studies Distro Area*

MATH 331-2 MENU: Abstract Algebra (1 Unit) Ring theory, including polynomial rings. Module theory, including canonical forms of operators on vector spaces. Students may not receive credit for both MATH 331-2 and MATH 330-2. Prerequisite: MATH 331-1 or consent of the department. *Formal Studies Distro Area*

MATH 331-3 MENU: Abstract Algebra (1 Unit) Field theory and Galois theory. Students may not receive credit for both MATH 331-3 and MATH 330-3. Prerequisite: MATH 331-2 or consent of the department. *Formal Studies Distro Area*

MATH 334-0 Linear Algebra: Second Course (1 Unit) Vector spaces. Linear maps. Eigenvalues, eigenvectors and invariant subspaces. Inner product spaces. Canonical forms of operators on real and complex vector spaces. Prerequisite: MATH 300-0; or MATH 291-2 and consent of the department. *Formal Studies Distro Area*

MATH 336-1 Introduction to the Theory of Numbers (1 Unit) Divisibility and prime numbers. Congruences. Quadratic reciprocity. Diophantine equations. Prerequisite: MATH 230-0 or MATH 281-1 or MATH 285-2 or MATH 290-2 or MATH 291-2 or ES_APPM 252-1. *Formal Studies Distro Area*

MATH 336-2 Introduction to the Theory of Numbers (1 Unit) Topics in analytic and algebraic number theory. Prerequisite: MATH 336-1. *Formal Studies Distro Area*

MATH 340-0 Geometry (1 Unit) Axioms for Euclidean geometry. Non-Euclidean geometry. Projective geometry. Introduction of coordinate systems from the axioms. Quadrics. Erlangen program. Introduction to plane algebraic curves. Prerequisite: MATH 300-0 or MATH 291-1 or consent of the instructor. *Formal Studies Distro Area*

MATH 342-0 Introduction to Differential Geometry (1 Unit) Differential geometry of curves and surfaces in three-dimensional space: curves, regular surfaces, the Gauss map, and additional topics as time permits. Prerequisites: MATH 234-0 or MATH 281-2 or MATH 285-3 or MATH 290-3 or MATH 291-3 or ES_APPM 252-2; and MATH 240-0 or MATH 281-3 or MATH 285-1 or MATH 290-1 or MATH 291-1 or GEN_ENG 205-1 or GEN_ENG 206-1. *Formal Studies Distro Area*

MATH 344-1 Introduction to Topology (1 Unit) Topological spaces, continuity, connectedness, compactness, countability and separation axioms. Prerequisite: MATH 320-1 or MATH 321-1. *Formal Studies Distro Area*

MATH 344-2 Introduction to Topology (1 Unit) The fundamental group. Classification of covering spaces. Additional topics as permits.

Prerequisites: MATH 344-1, and either MATH 330-1 or MATH 331-1. *Formal Studies Distro Area*

MATH 351-0 Fourier Analysis and Boundary Value Problems (1 Unit) Fourier series with applications to partial differential equations arising in physics and engineering. Students may not receive credit for both MATH 351-0 and any of MATH 381-0, MATH 360-2, or ES_APPM 311-2. Prerequisite: MATH 250-0 or MATH 281-3 or MATH 360-1 or GEN_ENG 206-4 or GEN_ENG 206-4. *Formal Studies Distro Area*

MATH 353-0 Qualitative Theory of Differential Equations (1 Unit) Qualitative theory of ordinary differential equations: linear systems, phase portraits, periodic solutions, stability theory, Lyapunov functions, and chaos. Students may not receive credit for both MATH 353-0 and MATH 360-2. Prerequisite: MATH 250-0 or MATH 281-3 or MATH 360-1 or GEN_ENG 205-4 or GEN_ENG 206-4. *Formal Studies Distro Area*

MATH 354-1 Chaotic Dynamical Systems (1 Unit) Chaotic phenomena in deterministic discrete dynamical systems, primarily through iteration of functions of one variable. Prerequisite: MATH 240-0 or MATH 281-3 or MATH 285-1 or MATH 290-1 or MATH 291-1 or GEN_ENG 205-1 or GEN_ENG 206-1. *Formal Studies Distro Area*

MATH 354-2 Chaotic Dynamical Systems (1 Unit) Iteration of functions of two or more variables, including the study of the horseshoe map, attractors, and the Henon map. Complex analytic dynamics, including the study of the Julia set and the Mandelbrot set. Prerequisite: MATH 354-1. *Formal Studies Distro Area*

MATH 360-1 MENU: Applied Analysis (1 Unit) Linear ordinary differential equations and their applications. Students may not receive credit for both MATH 360-1 and any of MATH 250-0, MATH 281-3, GEN_ENG 205-4, GEN_ENG 206-4. Prerequisite: MATH 290-3 or MATH 291-3 or consent of the instructor. *Formal Studies Distro Area*

MATH 360-2 MENU: Applied Analysis (1 Unit) Systems of linear ordinary differential equations and qualitative analysis of ordinary differential equations. Laplace transform. Linear partial differential equations. Fourier series and orthogonal functions. Applications. Students may not receive credit for both MATH 360-2 and MATH 381-0, MATH 351-0, or ES_APPM 311-2. Prerequisite: MATH 360-1 or consent of the instructor. *Formal Studies Distro Area*

MATH 366-1 Mathematical Models in Finance (1 Unit) Cash flow computations. Basic financial concepts (stocks, bonds, options, arbitrage, hedging) and put-call parity. Binomial tree models. Risk-neutral valuation. Random walk and Brownian motion as a tool of modeling fluctuations. Options pricing. Applications of the central limit theorem. The Black-Scholes formula and partial differential equation. Numerical approximations. Some familiarity with differential equations is desirable. Prerequisites: MATH 240-0 or MATH 281-3 or MATH 285-1 or MATH 290-1 or MATH 291-1 or GEN_ENG 205-1 or GEN_ENG 206-1; and MATH 310-1 or MATH 311-1 or MATH 314-0 or MATH 385-0 or STAT 320-1 or STAT 383-0 or IEMS 202-0 or EECS 302-0. *Formal Studies Distro Area*

MATH 368-0 Introduction to Optimization (1 Unit) Methods and concepts of optimization theory: linear programming, duality, convexity, and Kuhn-Tucker theory. Prerequisite: MATH 291-3; or MATH 300-0 and one of MATH 234-0, MATH 281-2, MATH 285-3, MATH 290-3, or ES_APPM 252-2. *Formal Studies Distro Area*

MATH 370-0 Mathematical Logic (1 Unit) Mathematical formulation and rigorous discussion of logical systems, particularly the propositional calculus and the functional calculi of first and second order. Well-formed formulae, formal languages, proofs, tautologies, effective procedures, deduction theorems, axiom schemata. Prerequisite: MATH 300-0 or MATH 291-3 or consent of the instructor. *Formal Studies Distro Area*

MATH 381-0 Fourier Analysis and Boundary Value Problems for ISP (1 Unit) Fourier series. Hilbert spaces and orthogonal functions. Parseval's theorem. Poisson summation formula and lattice points. Fourier integrals: Gaussian functions. Fourier inversion formula. Convolution. Sturm-Liouville theory. Applications to partial differential equations. Heat and wave equations. For ISP students. Students may not receive credit for both MATH 381-0 and any of MATH 351-0, MATH 360-2, or ES_APPM 311-2. Prerequisites: MATH 281-3 and PHYSICS 125-3. *Formal Studies Distro Area*

MATH 382-0 Complex Analysis and Group Theory for ISP (1 Unit) Complex analysis. Elements of group theory. For ISP students only. Students may not receive credit for both MATH 382-0 and any of MATH 325-0 or ES_APPM 311-2. Prerequisites: MATH 281-3 and PHYSICS 125-3. *Formal Studies Distro Area*

MATH 385-0 Probability and Statistics for MMSS (1 Unit) Probability theory and its applications in the social sciences. Students may not receive credit for both MATH 385-0 and any of MATH 310-1, MATH 311-1, MATH 314-0, STAT 320-1, STAT 383-0, IEMS 202-0, or EECS 302-0. Prerequisite: second-year standing in MMSS. *Formal Studies Distro Area*

MATH 386-1 Econometrics for MMSS (1 Unit) Econometric methods. Students may not receive credit for both MATH 386-1 and ECON 381-1. Prerequisite: MATH 385-0. *Formal Studies Distro Area*

MATH 386-2 Econometrics for MMSS (1 Unit) Econometric methods. Students may not receive credit for both MATH 386-2 and ECON 381-2. Prerequisite: MATH 386-1. *Formal Studies Distro Area*

MATH 395-0 Undergraduate Seminar (1 Unit) Topics in modern mathematics and relationships among different branches of mathematics. May be taken for only 1 unit of credit at a time but may be repeated for credit with change of topic. Prerequisite: consent of the department.

MATH 399-0 Independent Study (1 Unit) Independent learning under the direction of a faculty adviser. Students must obtain departmental approval for a plan of study before enrolling in MATH 399-0. Prerequisite: consent of the department.