MATHEMATICS

math.northwestern.edu

Mathematics is celebrated as the "Queen of the Sciences". It provides the language for science (both natural and social) to understand and predict the world around us. It is used to describe the precise interactions between particles at the atomic level, the motions of planets, the inner workings of computer algorithms and architectures, and the fluctuations in stock prices in modern markets. Today's deep discoveries in pure mathematics provide frameworks for the science and technology of tomorrow.

Mathematics studies the concepts of quantity and number, geometry and shape, and functions and change. It provides an approach to problem solving which emphasizes abstraction as a key tool, where rigor and intuition come together. Students majoring or minoring in mathematics have the opportunity to learn about its diverse applications, as well as acquiring an understanding of both the foundations and frontiers of the discipline.

The Department of Mathematics (https://www.math.northwestern.edu) offers a major and a minor in mathematics. The mathematics major and minor are 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 strong preparation who seek an early exposure to rigorous mathematics should consider participating in Mathematical Experience for Northwestern Undergraduates (MENU) (https://math.northwestern.edu/undergraduate/menu/). The department also encourages well-prepared undergraduate students to enroll in its graduate courses.

Course Recommendations
First-Year Placement

For information about course placement for first-year students, see the First Year Focus (https://www.math.northwestern.edu/undergraduate/first-year-focus/) webpage.

Mathematical Experience for Northwestern Undergraduates (MENU)

Mathematical Experience for Northwestern Undergraduates (MENU) (https://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 (https://www.math.northwestern.edu/undergraduate/advising/) is available to advise all MENU participants regardless of major.

The First Year

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

Course	Title
MATH 290-1	MENU: Linear Algebra and Multivariable Calculus
& MATH 290-2	and MENU: Linear Algebra and Multivariable Calculus
& MATH 290-3	
	and MENU: Linear Algebra and Multivariable Calculus
or MATH 291-1	MENU: Intensive Linear Algebra and Multivariable Calculus
& MATH 291-2	and MENU: Intensive Linear Algebra and Multivariable Calculus
& MATH 291-3	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. 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 (https://www.math.northwestern.edu/undergraduate/advising/).

MENU and MATH 226-0

MENU participants who do not have credit for MATH 226-0 should consider taking MATH 226-0, which is a prerequisite for most further courses in differential equations, probability, and analysis. MENU participants who anticipate taking ECON 381-1 should note that MATH 314-0 is prerequisite for ECON 381-1, and MATH 226-0 is prerequisite for MATH 314-0. MATH 226-0 is also a required course for the mathematics major, the mathematics minor, the statistics major, and the statistics minor.

Beyond the First Year

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

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

or they may enroll in other advanced mathematics courses.

Participating in MENU

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 (https://www.math.northwestern.edu/undergraduate/advising/) 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 220-1 or MATH 220-2 may consult the Director of MENU (https://www.math.northwestern.edu/undergraduate/advising/) about continuing their studies of mathematics in MENU. Further information is available at Mathematical Experience for Northwestern Undergraduates (MENU) (https://math.northwestern.edu/undergraduate/menu/).

Mathematics and Computer Science

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

Course	Title
MATH 300-0	Foundations of Higher Mathematics
MATH 306-0	Combinatorics & Discrete Mathematics
MATH 308-0	Graph Theory
MATH 310-1 & MATH 310-2	Probability and Stochastic Processes and Probability and Stochastic Processes
or MATH 311-1 & MATH 311-2	MENU: Probability and Stochastic Processes and MENU: Probability and Stochastic Processes
MATH 334-0	Linear Algebra: Second Course
MATH 336-1	Introduction to the Theory of Numbers
COMP_SCI 336-0	Design & Analysis of Algorithms
COMP_SCI 339-0	Introduction to Database Systems
COMP_SCI 349-0	Machine Learning
IEMS 303-0	Statistics

Mathematics and Economics

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

Course	Title
MATH 314-0 & MATH 310-2 & MATH 310-3	Probability and Statistics for Econometrics and Probability and Stochastic Processes and Probability and Stochastic Processes
or MATH 314-0 & MATH 311-2 & MATH 311-3	Probability and Statistics for Econometrics and MENU: Probability and Stochastic Processes and MENU: Probability and Stochastic Processes
MATH 320-1 & MATH 320-2 & MATH 320-3	Real Analysis and Real Analysis and Real Analysis
or MATH 321-1 & MATH 321-2 & MATH 321-3	MENU: Real Analysis and MENU: Real Analysis and MENU: Real Analysis
ECON 331-0	Economics of Risk and Uncertainty
ECON 380-1 & ECON 380-2	Game Theory and Game Theory
ECON 381-1 & ECON 381-2	Econometrics and Econometrics

Enrolling in MATH 311-2 after MATH 314-0 requires permission from the Department of Mathematics (https://www.math.northwestern.edu).

Actuarial Science

The following courses and course sequences are essential for students pursuing a credential in actuarial science:

Course	Title
ECON 381-1 & ECON 381-2	Econometrics and Econometrics
or MATH 386-1 & MATH 386-2	Econometrics for MMSS and Econometrics for MMSS
ECON 360-1	Foundations of Corporate Finance Theory
or KELLG_FE 310-0	Principles of Finance
or CIV_ENV 205-0	Economics and Finance for Engineers
ECON 310-1	Microeconomics
ECON 311-0	Macroeconomics

To prepare for Exam P by the Society of Actuaries or Exam 1 by the Casualty Actuarial Society students should consider the following course sequences:

Course	Title
MATH 314-0 & MATH 310-2 & MATH 310-3	Probability and Statistics for Econometrics and Probability and Stochastic Processes and Probability and Stochastic Processes
or MATH 314-0 & MATH 311-2 & MATH 311-3	Probability and Statistics for Econometrics and MENU: Probability and Stochastic Processes and MENU: Probability and Stochastic Processes

Enrolling in MATH 311-2 after MATH 314-0 requires permission from the Department of Mathematics (https://www.math.northwestern.edu).

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

Course	Title
MATH 366-0	Mathematical Models in Finance
BUS_INST 301-0	Accounting
STAT 320-2 & STAT 320-3	Statistical Theory & Methods 2 and Statistical Theory & 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
STAT 359-0	Topics in Statistics

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 in Mathematics (https://www.math.northwestern.edu/undergraduate/advising/) may waive prerequisites for mathematics courses. No waived prerequisite course is eligible for credit after a student completes another course for which it is prerequisite without permission from the Department of Mathematics (https://www.math.northwestern.edu). MATH 100-0 and MATH 110-0 are not available for credit after completing a course at the 200 level or higher. See the course descriptions for other restrictions. Students following the Undergraduate Catalog 2022-2023 or earlier edition may be able to satisfy the Formal Studies distribution requirement with a single high-level mathematics course; check catalog archives for policies.

MATH 100-0 Quantitative Reasoning (1 Unit)   Analyzing topical, real-life problems from a quantitative perspective. Solving multistep problems using elementary algebra, probability, and statistics. Students may not receive credit for MATH 100-0 after earning credit for a 200-level MATH course or higher. *Empirical and Deductive Reasoning Foundational Dis Formal Studies Distro Area*

MATH 100-BR Quantitative Reasoning (0.5 Unit)   For participants in Bridge I summer program. Analyzing topical, real-life problems from a quantitative perspective. Solving multistep problems using elementary algebra, probability, and statistics. Taken with HUM 100-1-BR.

MATH 105-7 College Seminar (1 Unit)   Small, writing and discussion-oriented course exploring a specific topic or theme, and introducing skills necessary to thriving at Northwestern. Not eligible to be applied towards a WCAS major or minor except where specifically indicated.

MATH 105-8 First-Year Writing Seminar (1 Unit)   Small, writing and discussion-oriented course exploring a specific topic or theme, and focused on the fundamentals of effective, college-level written communication. Not eligible to be applied towards a WCAS major or minor except where specifically indicated.

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. Students may not receive credit for MATH 110-0 after earning credit for a 200-level MATH course or higher. *Formal Studies Distro Area*

MATH 202-0 Finite Mathematics (1 Unit)   Selected topics from elementary linear algebra and its applications, finite probability, and elementary statistics. For students majoring in the behavioral sciences. *Empirical and Deductive Reasoning Foundational Dis 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 (former), MATH 213-0 (former), MATH 214-0 (former), MATH 218-1, MATH 218-2, MATH 218-3, MATH 220-0 (former), MATH 220-1, MATH 220-2, MATH 224-0 (former), or MATH 226-0. Not suitable for students planning to major in mathematics, the natural sciences, or economics. *Empirical and Deductive Reasoning Foundational Dis Formal Studies Distro Area*

MATH 218-1 Single-Variable Calculus with Precalculus (1 Unit)   Functions and graphs. Limits. Continuity. Differentiation. Linearization. Students may not receive credit for both MATH 218-1 and any of MATH 211-0, MATH 212-0 (former), MATH 220-0 (former), or MATH 220-1. Prerequisite: consent of the department. *Empirical and Deductive Reasoning Foundational Dis Formal Studies Distro Area*

MATH 218-2 Single-Variable Calculus with Precalculus (1 Unit)   Extreme value theorem, mean value theorem, and curve-sketching. Related rates. Optimization. Transcendental and inverse functions. Students may not receive credit for both MATH 218-2 and any of MATH 211-0, MATH 212-0 (former), MATH 220-0 (former), or MATH 220-1. Prerequisite: MATH 218-1 or consent of the department. *Empirical and Deductive Reasoning Foundational Dis Formal Studies Distro Area*

MATH 218-3 Single-Variable Calculus with Precalculus (1 Unit)   Definite integrals, antiderivatives, and the fundamental theorem of calculus. Areas and volumes. Techniques of integration, numerical integration, and improper integrals. First-order linear and separable ordinary differential equations. Students may not receive credit for both MATH 218-3 and any of MATH 213-0 (former), MATH 220-2, or MATH 224-0 (former).

Prerequisite: MATH 218-2 or consent of the department. *Empirical and Deductive Reasoning Foundational Dis Formal Studies Distro Area*

MATH 218-SG-1 Peer-Guided Study Group: Single-Variable Calculus with Precalculus (0 Unit)   Peer-guided study group for students enrolled in MATH 218-1. Meets weekly in small groups with a peer facilitator, to collaboratively review material, solve practice problems, and clarify concepts. Enrollment optional. Graded S/U.

MATH 218-SG-2 Peer-Guided Study Group: Single-Variable Calculus with Precalculus (0 Unit)   Peer-guided study group for students enrolled in MATH 218-2. Meets weekly in small groups with a peer facilitator, to collaboratively review material, solve practice problems, and clarify concepts. Enrollment optional. Graded S/U.

MATH 218-SG-3 Peer-Guided Study Group: Single-Variable Calculus with Precalculus (0 Unit)   Peer-guided study group for students enrolled in MATH 218-3. Meets weekly in small groups with a peer facilitator, to collaboratively review material, solve practice problems, and clarify concepts. Enrollment optional. Graded S/U.

MATH 220-1 Single-Variable Differential Calculus (1 Unit)   Limits. Differentiation. Linear approximation and related rates. Extreme value theorem, mean value theorem, and curve-sketching. Optimization. Students may not receive credit for both MATH 220-1 and any of MATH 211-0, MATH 212-0 (former), MATH 213-0 (former), MATH 218-1, MATH 218-2, or MATH 220-0 (former). *Empirical and Deductive Reasoning Foundational Dis Formal Studies Distro Area*

MATH 220-2 Single-Variable Integral Calculus (1 Unit)   Definite integrals, antiderivatives, and the fundamental theorem of calculus. Transcendental and inverse functions. Areas and volumes. Techniques of integration, numerical integration, and improper integrals. First-order linear and separable ordinary differential equations. Students may not receive credit for both MATH 220-2 and any of MATH 213-0 (former), MATH 214-0 (former), MATH 218-3, or MATH 224-0 (former). Prerequisite: MATH 218-2 or MATH 220-0 (former) or MATH 220-1. *Empirical and Deductive Reasoning Foundational Dis Formal Studies Distro Area*

MATH 220-MG-1 Midquarter Study Group: Math 220-1 Single-Variable Diff Calculus (0 Unit)   Peer-guided study group for students enrolled in MATH 220-1. Meets weekly, starting at midquarter, in small groups with a peer facilitator to collaboratively review material, solve practice problems, and clarify concepts. Enrollment optional. Graded S/U.

MATH 220-MG-2 Midquarter Study Group: MATH 220-2 Single-Variable Integral Calculus (0 Unit)   Peer-guided study group for students enrolled in MATH 220-2. Meets weekly, starting at midquarter, in small groups with a peer facilitator to collaboratively review material, solve practice problems, and clarify concepts. Enrollment optional. Graded S/U.

MATH 220-SG-1 Peer-Guided Study Group: Single-Variable Differential Calculus (0 Unit)   Peer-guided study group for students enrolled in MATH 220-1. Meets weekly in small groups with a peer facilitator to collaboratively review material, solve practice problems, and clarify concepts. Enrollment optional. Graded S/U.

MATH 220-SG-2 Peer-Guided Study Group: Single-Variable Integral Calculus (0 Unit)   Peer-guided study group for students enrolled in MATH 220-2. Meets weekly in small groups with a peer facilitator to collaboratively review material, solve practice problems, and clarify concepts. Enrollment optional. Graded S/U.

MATH 226-0 Sequences and Series (1 Unit)   Infinite sequences. Infinite series and convergence tests. Power series, Taylor series, Taylor polynomials and error. Complex numbers. Second-order linear ordinary differential equations and power series solutions. Students may not receive credit for both MATH 226-0 and any of MATH 214-0 (former),

MATH 224-0 (former), or MATH 281-2. Prerequisite: MATH 218-3 or MATH 220-2. *Empirical and Deductive Reasoning Foundational Dis Formal Studies Distro Area*

MATH 228-1 Multivariable Differential Calculus for Engineering (1 Unit) Vectors, vector functions, partial derivatives, Taylor polynomials, and optimization. Emphasis on engineering applications. For McCormick School of Engineering students only. Students may not receive credit for both MATH 228-1 and any of MATH 230-0 (former), MATH 230-1, MATH 281-1, MATH 285-2, MATH 290-2, MATH 291-2, or ES_APPM 252-1. Prerequisite: MATH 218-3 or MATH 214-0 (former) or MATH 220-2 or MATH 224-0 (former). *Empirical and Deductive Reasoning Foundational Dis Formal Studies Distro Area*

MATH 228-2 Multivariable Integral Calculus for Engineering (1 Unit) Multiple integration: double integrals, triple integrals, and change of variables. Vector calculus: vector fields, line integrals, surface integrals, curl and divergence, Green's theorem, Stokes' theorem, and the divergence theorem. Emphasis on engineering applications. For McCormick School of Engineering students only. Students may not receive credit for both MATH 228-2 and any of MATH 230-2, MATH 234-0 (former), MATH 281-2, MATH 285-3, MATH 290-3, MATH 291-3, or ES_APPM 252-2. Prerequisite: MATH 228-1 or MATH 230-0 (former) or MATH 230-1 or MATH 281-1 or MATH 285-2 or MATH 290-2 or MATH 291-2 or ES_APPM 252-1. *Empirical and Deductive Reasoning Foundational Dis Formal Studies Distro Area*

MATH 228-SG-1 Peer-Guided Study Group: Multivariable Calculus for Engineering (0 Unit) Peer-guided study group for students enrolled in MATH 228-1. Meets weekly in small groups with a peer facilitator to collaboratively review material, solve practice problems, and clarify concepts. Enrollment optional. Graded S/U.

MATH 230-1 Multivariable Differential Calculus (1 Unit) Vectors, vector functions, partial derivatives, and optimization. Not open to students in the McCormick School of Engineering. Students may not receive credit for both MATH 230-1 and any of MATH 228-1, MATH 230-0 (former), MATH 281-1, MATH 285-2, MATH 290-2, MATH 291-2, or ES_APPM 252-1. Prerequisite: MATH 218-3 or MATH 214-0 (former) or MATH 220-2 or MATH 224-0 (former). *Empirical and Deductive Reasoning Foundational Dis Formal Studies Distro Area*

MATH 230-2 Multivariable Integral 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. Not open to students in the McCormick School of Engineering. Students may not receive credit for both MATH 230-2 and any of MATH 228-2, MATH 234-0 (former), MATH 281-2, MATH 285-3, MATH 290-3, MATH 291-3, or ES_APPM 252-2. Prerequisite: MATH 228-1 or MATH 230-0 (former) or MATH 230-1 or MATH 281-1 or MATH 285-2 or MATH 290-2 or MATH 291-2 or ES_APPM 252-1. *Empirical and Deductive Reasoning Foundational Dis Formal Studies Distro Area*

MATH 230-MG-1 Midquarter Study Group: Math 230-1 Multivariable Differential Calculus (0 Unit) Peer-guided study group for students enrolled in MATH 230-1. Meets weekly, starting at midquarter, in small groups with a peer facilitator to collaboratively review material, solve practice problems, and clarify concepts. Enrollment optional. Graded S/U.

MATH 230-SG-1 Peer-Guided Study Group: Multivariable Differential Calculus (0 Unit) Peer-guided study group for students enrolled in MATH 230-1. Meets weekly in small groups with a peer facilitator to collaboratively review material, solve practice problems, and clarify concepts. Enrollment optional. Graded S/U.

MATH 235-0 Series and Multiple Integrals (1 Unit) Sequences and series, and convergence tests. Power series, Taylor polynomials and error. Double integrals, triple integrals, and change of variables. Students may receive credit for only one of MATH 235#0, MATH 226#0, or STAT 228#0. Prerequisite: MATH 218#3 or MATH 220#2, and MATH 228#1 or MATH 230#1 or MATH 281#1 or MATH 285#2 or MATH 290#2 or MATH 291#2 or ES_APPM 252#1. *Empirical and Deductive Reasoning Foundational Dis 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 230-1 or MATH 230-0 (former) or MATH 281-1 or ES_APPM 252-1. *Empirical and Deductive Reasoning Foundational Dis 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 226-0 or MATH 281-2; and MATH 228-2 or MATH 230-2 or MATH 234-0 (former) 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. *Empirical and Deductive Reasoning Foundational Dis 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 228-1, MATH 230-0 (former), MATH 230-1, MATH 285-2, MATH 290-2, MATH 291-2, or ES_APPM 252-1. Prerequisite: first-year standing in ISP. *Empirical and Deductive Reasoning Foundational Dis 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 226-0, MATH 228-2, MATH 230-2, MATH 234-0 (former), MATH 285-3, MATH 290-3, MATH 291-3, or ES_APPM 252-2. Prerequisite: MATH 281-1. *Empirical and Deductive Reasoning Foundational Dis 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. *Empirical and Deductive Reasoning Foundational Dis 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. *Empirical and Deductive Reasoning Foundational Dis 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 228-1, MATH 230-0 (former), MATH 230-1,

MATH 281-1, MATH 290-2, MATH 291-2, or ES_APPM 252-1. Prerequisite: MATH 285-1. *Empirical and Deductive Reasoning Foundational Dis 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 228-2, MATH 230-2, MATH 234-0 (former), MATH 281-2, MATH 290-3, MATH 291-3, or ES_APPM 252-2. Prerequisite: MATH 285-2. *Empirical and Deductive Reasoning Foundational Dis 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. *Empirical and Deductive Reasoning Foundational Dis 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 228-1, MATH 230-0 (former), MATH 230-1, MATH 281-1, MATH 285-2, MATH 291-2, or ES_APPM 252-1. Prerequisite: MATH 290-1. *Empirical and Deductive Reasoning Foundational Dis 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 228-2, MATH 230-2, MATH 234-0 (former), MATH 281-2, MATH 285-3, MATH 291-3, or ES_APPM 252-2. Prerequisite: MATH 290-2. *Empirical and Deductive Reasoning Foundational Dis 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, vector spaces, and subspaces. 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. *Empirical and Deductive Reasoning Foundational Dis Formal Studies Distro Area*

MATH 291-2 MENU: Intensive Linear Algebra and Multivariable Calculus (1 Unit) Linear algebra: orthogonality, determinants, eigenvectors, and symmetric matrices. 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 228-1, MATH 230-0 (former), MATH 230-1, MATH 281-1, MATH 285-2, MATH 290-2, or ES_APPM 252-1. Prerequisite: MATH 291-1. *Empirical and Deductive Reasoning Foundational Dis Formal Studies Distro Area*

MATH 291-3 MENU: Intensive Linear Algebra and Multivariable Calculus (1 Unit) Multivariable differential calculus: optimzation. 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 228-2, MATH 230-2, MATH 234-0 (former), MATH 281-2, MATH 285-3, MATH 290-3, or ES_APPM 252-2. Prerequisite: MATH 291-2. *Empirical and Deductive Reasoning Foundational Dis 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. 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 300-BR Foundations of Higher Mathematics (1 Unit)
For participants in the Causeway Postbaccalaureate Program only. Introduction to fundamental mathematical structures, including sets, functions, equivalence relations, and cardinal numbers. Elementary logic and proof techniques. Additional topics selected by the instructor.

MATH 306-0 Combinatorics & Discrete Mathematics (1 Unit)
Discrete mathematics, inductive reasoning, counting problems, binomial coefficients and Pascal's triangle, Fibonacci numbers, set and integer 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.
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 ELEC_ENG 302-0.
Prerequisite or corequisite: MATH 226-0 or MATH 281-2; and MATH 228-2 or MATH 230-2 or MATH 234-0 (former), 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 or MATH 314-0 or MATH 385-0 or STAT 320-1 or STAT 383-0 or IEMS 202-0 or ELEC_ENG 302-0.
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 ELEC_ENG 302-0.
Prerequisite: MATH 226-0 or MATH 281-2; and MATH 291-3, or MATH 300-0 and any one of MATH 290-3, MATH 281-2, MATH 285-3

or ES_APPM 252-2; or consent of the department. Recommended: MATH 320-1 or MATH 321-1.
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 ELEC_ENG 302-0. Prerequisite or corequisite: MATH 226-0 or MATH 281-2; and MATH 228-2 or MATH 230-2 or MATH 234-0 (former) or MATH 281-1 or MATH 285-3 or MATH 290-3 or MATH 291-3 or ES_APPM 252-2.
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 226-0 or MATH 281-2; and 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: 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. Students may not receive credit for both MATH 325-0 and either MATH 382-0 or ES_APPM 312-0.
Prerequisites: MATH 226-0 or MATH 281-2; and MATH 228-2 or MATH 230-2 or MATH 234-0 (former) 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 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, 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 226-0 or MATH 281-3; and MATH 228-2 or MATH 230-2 or MATH 234-0 (former) 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 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.
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.
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: 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.
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.
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.
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 228-1 or MATH 230-1 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.
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 226-0 or MATH 281-2; and MATH 228-2 or MATH 230-2 or MATH 234-0 (former) 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 354-0 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 360-1 MENU: Applied Analysis (1 Unit)
Linear ordinary differential equations, systems of linear ordinary differential equations, and 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 226-0 or MATH 281-2; and MATH 290-3 or MATH 291-3.
Formal Studies Distro Area

MATH 360-2 MENU: Applied Analysis (1 Unit)
Qualitative analysis of systems of ordinary differential equations. Linear partial differential equations. Fourier series and orthogonal functions. Applications. Students may not receive credit for both MATH 360-2 and any of MATH 381-0, MATH 351-0, or ES_APPM 311-2.
Prerequisite: MATH 360-1.
Formal Studies Distro Area

MATH 366-0 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 for 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 ELEC_ENG 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.
Prerequisites: MATH 226-0 or MATH 281-2; and MATH 291-3, or MATH 300-0 and one of MATH 228-2, MATH 230-2, MATH 234-0 (former), 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 only. 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 for ISP (1 Unit)   Complex numbers. Analytic functions. Cauchy's theorem and the Cauchy integral formula. Series. Residues. For ISP students only. Students may not receive credit for both MATH 382-0 and either MATH 325-0 or ES_APPM 312-0. 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 ELEC_ENG 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.