

# Department of Mathematical Sciences

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Mathematics provides much of the language and quantitative underpinnings of the natural and social sciences, and mathematical scientists have been responsible for the development of many of the most commonly used tools in business management as well as for laying the foundation for computational and computer science. The name of the Department of Mathematical Sciences reflects its tradition of outstanding research and teaching of applicable mathematics relating to these areas. Indeed, the Department contains highly ranked research groups in Applied Mathematics, Discrete Mathematics, Logic, and Mathematical Finance. These research strengths are reflected in the variety of options that the Department provides for its undergraduate majors.

The Department offers a B.S. degree in Mathematical Sciences. Concentrations within the degree include Mathematical Sciences, Operations Research and Statistics, Statistics, Discrete Mathematics and Logic, and Computational and Applied Mathematics.

The Mathematical Sciences concentration is the least structured of our programs, in recognition of the wide variety of interests that can be productively coupled with the study of mathematical sciences. It can be an appropriate choice for students planning for graduate study in mathematics or seeking to design their curriculum to take advantage of the many opportunities for a second major from another department in the University.

The Operations Research and Statistics concentration prepares students to enter the area of optimization. Mathematicians with a background in operations research are especially valuable in such diverse activities as project planning, production scheduling, market forecasting and finance. Such applications are found in virtually all industrial and governmental settings.

The Statistics concentration prepares students to contribute to a wide variety of research areas. Applications range from experimental design and data analysis in the physical and social sciences, medicine and engineering, to modeling and forecasting in business and government, to actuarial applications in the financial and insurance industries. This is also a useful second major for students planning for graduate study and research in subject areas requiring a strong statistical background.

The Discrete Mathematics and Logic concentration provides a background in discrete mathematics, mathematical logic, and theoretical computer science. This concentration prepares the student to do research in these and related fields, or to apply their ideas elsewhere.

Finally, the Computational and Applied Mathematics concentration provides the background needed to support the computational and mathematical analysis needs of a wide variety of businesses and industries and is well suited to students with an interest in the physical sciences and engineering.

The Department places great emphasis on the advising of students. This is critical if students are to make the most of their years at the University. Students are urged to work carefully with their advisor and other faculty to formulate their degree programs. Study abroad is encouraged, and an interested student should investigate the opportunities available in the Undergraduate Options (<http://coursecatalog.web.cmu.edu/aboutcmu/undergraduateoptions/>) section of the catalog.

## Special Options

The Department offers special opportunities for the exceptionally well-prepared and intellectually ambitious student. These options are available to students from any department in the University.

## Matrix Theory and Vector Analysis

For selected freshmen entering the University, the department offers the fall/spring sequence of 21-242 Matrix Theory and 21-269 Vector Analysis,

which include a rigorous introduction to proofs and abstract mathematics. Typically, a student choosing this sequence has mastered the operational aspects of high school mathematics and now seeks a deeper conceptual understanding.

- 21-242 Matrix Theory is an honors version of 21-241 Matrices and Linear Transformations .
- 21-269 Vector Analysis is an honors version of 21-268 Multidimensional Calculus .

Admission to 21-242 Matrix Theory is based on an assessment exam taken at the start of the freshman year. Admission to 21-269 Vector Analysis is based on a student's performance in 21-242 Matrix Theory, and on other courses taken in the fall semester.

## Mathematical Studies

The sequence of undergraduate honors courses continues with the Mathematical Studies courses, aimed primarily at sophomores. These highly demanding courses provide excellent preparation for graduate study, with many of the participants taking graduate courses as early as their junior year. Students will be expected to master material at a high level of abstraction, and to work on very challenging problems. The typical enrollment of about 15 students allows for close contact with the instructors.

- 21-235 Mathematical Studies Analysis I is an honors version of 21-355 Principles of Real Analysis I.
- 21-237 Mathematical Studies Algebra I is an honors version of 21-373 Algebraic Structures.
- 21-236 Mathematical Studies Analysis II is an honors version of 21-356 Principles of Real Analysis II.
- 21-238 Mathematical Studies Algebra II is an honors version of 21-341 Linear Algebra.

Admission to Mathematical Studies is by invitation. Interested students should apply during the spring of their freshman year. Applicants are not absolutely required to have taken 21-242 Matrix Theory or 21-269 Vector Analysis, and may be admitted on the basis of exceptionally strong performance in non-honors mathematics courses.

It is possible to take only the algebra courses or only the analysis courses. Admission to 21-236 Mathematical Studies Analysis II requires a grade of B or better in 21-235 Mathematical Studies Analysis I, and similarly, admission to 21-238 Mathematical Studies Algebra II requires a grade of B or better in 21-237 Mathematical Studies Algebra I.

## Interdisciplinary Programs

Several interdisciplinary options enable a student to combine mathematics with other disciplines.

- The Bachelor of Science and Arts (<http://coursecatalog.web.cmu.edu/intercollegeprograms/bxaintercollege/#bachelorofscienceandartsdegreeprogram>) program allows a student to combine mathematics with study in any of the five schools in the College of Fine Arts.
- The Bachelor of Science in Mathematics and Economics (<http://coursecatalog.web.cmu.edu/schools-colleges/tepper/undergraduateeconomicsprogram/#bsineconomicsandmathematicalsciences>) is a flexible program which allows students to develop depth in both fields of study. Note: for students whose home college is Dietrich College, this major is known as the Bachelor of Science in Economics and Mathematical Sciences.
- Finally, a joint program with the Heinz College of Public Policy and Management and the Tepper School of Business leads to the degree Bachelor of Science in Computational Finance (<http://coursecatalog.web.cmu.edu/intercollegeprograms/#bachelorofscienceincomputationalfinance>).

## Curriculum

We provide a list of the requirements for each concentration in the B.S. degree in Mathematical Sciences. Any exceptions to the elective requirements require prior approval from the student's academic advisor.

A student preparing for graduate study should also consider undertaking independent work. The Department offers 21-410 Research Topics in Mathematical Sciences and 21-599 Undergraduate Reading and

Research for this purpose. At most, nine units of 21-410 or 21-599 credit can be applied toward depth elective requirements, and to do so requires prior approval from the student's academic advisor. Courses numbered 21-600 and above carry graduate credit, with courses at the 600-level designed as transitional courses to graduate study.

For each concentration, a suggested schedule that includes general education requirements can be found here (<https://www.cmu.edu/math/undergrad/degrees.html>). For a list of courses required for all Mellon College of Science students, see the MCS General Education Requirements (<http://coursecatalog.web.cmu.edu/schools-colleges/melloncollegeofscience/#generaleducationrequirementstext>).

By default, students must fulfill all of the requirements of the catalog of the year they entered CMU. Students who wish to be considered for a subsequent catalog may submit a request to their academic advisor.

(must be at the 36-300 level or above and have at least 36-225 as a prerequisite) electives.

### MCS General Education (required)

MCS humanities, social sciences, and science core (114 units)

Minimum number of units required for degree: 360

### Mathematical Sciences Electives for Students Intending Graduate Study

Students preparing for graduate study in mathematics should consider the following courses as Mathematical Sciences Electives, choosing among them according to the desired area of graduate study.

Courses	Units
21-301 Combinatorics	9
21-326 Markov Chains: Theory, Simulation and Applications	9
21-360 Differential Geometry of Curves and Surfaces	9
21-371 Functions of a Complex Variable	9
21-374 Field Theory	9
21-441 Number Theory	9
21-484 Graph Theory	9
21-602 Introduction to Set Theory I	12
21-603 Model Theory I	12
21-610 Algebra I	12
21-623 Complex Analysis	12
21-624 Descriptive Set Theory	12
21-630 Ordinary Differential Equations	12
21-632 Introduction to Differential Equations	12
21-640 Introduction to Functional Analysis	12
21-651 General Topology	12
21-660 Introduction to Numerical Analysis I	12
21-701 Discrete Mathematics	12
21-720 Measure and Integration	12
21-721 Probability	12
21-723 Advanced Real Analysis	12
21-737 Probabilistic Combinatorics	12
21-738 Extremal Combinatorics	12

## B.S. in Mathematical Sciences

This program is the most flexible available to our majors, where students choose eight electives within the major and at least seven free electives, giving them the opportunity to design a program to suit their individual interests and goals.

The requirements for the B.S. in Mathematical Sciences are:

### Mathematical Sciences Courses (required)

The alternative courses 21-242, 21-261, and 21-268 (or 21-269) are particularly recommended for a student planning to pursue graduate work.

Courses	Units
21-120 Differential and Integral Calculus	10
21-122 Integration and Approximation	10
21-127 Concepts of Mathematics	12
or 21-128 Mathematical Concepts and Proofs	
21-201 Undergraduate Colloquium	1
21-228 Discrete Mathematics	9-12
or 15-251 Great Ideas in Theoretical Computer Science	
21-241 Matrices and Linear Transformations	11
or 21-242 Matrix Theory	
21-259 Calculus in Three Dimensions	10-12
or 21-266 Vector Calculus using Matrix Algebra	
or 21-268 Multidimensional Calculus	
or 21-269 Vector Analysis	
21-260 Differential Equations	9-10
or 21-261 Introduction to Ordinary Differential Equations	
or 33-231 Physical Analysis	
21-325 Probability	9-12
or 15-259 Probability and Computing	
or 36-218 Probability Theory for Computer Scientists	
21-341 Linear Algebra	9
21-355 Principles of Real Analysis I	9-12
or 21-455 Intermediate Real Analysis I	
21-356 Principles of Real Analysis II	9-10
or 21-456 Intermediate Real Analysis II	
21-373 Algebraic Structures	9

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### Computer Science Courses (required)

Courses	Units
15-110 Principles of Computing	10-12
or 15-112 Fundamentals of Programming and Computer Science	
or 02-120 Programming for Scientists	

**10-12**

### DEPTH ELECTIVES (REQUIRED)

#### Seventy-two total units

- Forty-five units of Mathematical Sciences Electives (at the 21-300 level or above or 21-270 or 21-292).
- Twenty-seven units of Mathematical Sciences (at the 21-300 level or above or 21-270 or 21-292), or Computer Science (at the 15-200 level or above), or Physics (at the 33-300 level or above), or Statistics

## B.S. in Mathematical Sciences (Operations Research and Statistics)

An operations research professional employs quantitative and computational skills toward enhancing the function of an organization or process. Students choosing this concentration will develop problem-solving abilities in mathematical and statistical modeling and computer-based simulation in areas such as network design, transportation scheduling, allocation of resources and optimization. In addition to courses in mathematics and statistics, a basic background in economics and accounting is included. Since problems in business and industry are often solved by teams, the curriculum typically includes group projects. Students choosing this concentration may not pursue an additional minor in Statistics in the Dietrich College of Humanities and Social Sciences.

The requirements for the concentration in Operations Research and Statistics are:

### Mathematical Sciences Courses (required)

The alternative courses 21-242, 21-261, and 21-268 (or 21-269) are particularly recommended for a student planning to pursue graduate work.

Courses	Units
21-120 Differential and Integral Calculus	10
21-122 Integration and Approximation	10
21-127 Concepts of Mathematics	12
or 21-128 Mathematical Concepts and Proofs	
21-201 Undergraduate Colloquium	1
21-228 Discrete Mathematics	9-12
or 15-251 Great Ideas in Theoretical Computer Science	
21-241 Matrices and Linear Transformations	11

or 21-242	Matrix Theory	
21-259	Calculus in Three Dimensions	10-12
or 21-266	Vector Calculus using Matrix Algebra	
or 21-268	Multidimensional Calculus	
or 21-269	Vector Analysis	
21-260	Differential Equations	9-10
or 21-261	Introduction to Ordinary Differential Equations	
or 33-231	Physical Analysis	
21-292	Operations Research I	9
21-369	Numerical Methods	12
21-393	Operations Research II	9

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### Statistics Courses (required)

Courses		Units
21-325	Probability	9-12
or 15-259	Probability and Computing	
or 36-218	Probability Theory for Computer Scientists	
36-226	Introduction to Statistical Inference	9
36-401	Modern Regression	9
36-402	Advanced Methods for Data Analysis	9
36-410	Introduction to Probability Modeling	9

**45-48**

### Economics, Business, and Computer Science Courses (required)

Courses		Units
15-110	Principles of Computing	10
70-122	Introduction to Accounting	9
73-102	Principles of Microeconomics	9
73-103	Principles of Macroeconomics	9
73-230	Intermediate Microeconomics	9
or 73-240	Intermediate Macroeconomics	

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### Depth Electives (required)

**Forty-five units** of depth electives, to be chosen from the list below, or any other Mathematical Sciences Elective (at the 21-300 level or above or 21-270 or 21-292). **At least nine of these units must be Mathematical Sciences Electives (21-XXX)**

The courses 21-355 and 21-455 are particularly recommended for a student planning to pursue graduate work.

Courses		Units
10-301	Introduction to Machine Learning	12
or 10-315	Introduction to Machine Learning (SCS Majors)	
15-122	Principles of Imperative Computation	12
15-150	Principles of Functional Programming	12
15-210	Parallel and Sequential Data Structures and Algorithms	12
21-236	Mathematical Studies Analysis II	12
21-270	Introduction to Mathematical Finance	9
21-301	Combinatorics	9
21-321	Interactive Theorem Proving	9
21-326	Markov Chains: Theory, Simulation and Applications	9
21-341	Linear Algebra	9
21-355	Principles of Real Analysis I	9-12
or 21-455	Intermediate Real Analysis I	
21-356	Principles of Real Analysis II	9-10
or 21-456	Intermediate Real Analysis II	
21-370	Discrete Time Finance	9
21-373	Algebraic Structures	9
21-378	Mathematics of Fixed Income Markets	9
21-420	Continuous-Time Finance	9
21-484	Graph Theory	9
36-46X	Special Topics (Statistics)	9-12
36-47X	Special Topics (Statistics)	9-12

70-371	Operations Management	9
70-460	Mathematical Models for Consulting	9
70-467	Machine Learning for Business Analytics	9
70-469	End to End Business Analytics	9
70-471	Supply Chain Management	9

### MCS General Education (required)

MCS humanities, social sciences, and science core (114 units)

Note that 73-102, 73-103, 73-230, and 73-240 satisfy Nontechnical Elective (<http://coursecatalog.web.cmu.edu/schools-colleges/melloncollegeofscience/#generaleducationrequirementstext>) requirements from the MCS general education core.

Minimum number of units required for degree: 360

## B.S. in Mathematical Sciences (Statistics)

Statistics is concerned with the process by which inferences are made from data. Statistical methods are essential to research in a wide variety of scientific disciplines. For example, principles of experimental design that assist chemists in improving their yields also help poultry farmers grow bigger chickens. Similarly, time series analysis is used to better understand radio waves from distant galaxies, hormone levels in the blood, and concentrations of pollutants in the atmosphere. This diversity of application is an exciting aspect of the field, and it is one reason for the current demand for well-trained statisticians.

The Statistics concentration is jointly administered by the Department of Mathematical Sciences and the Department of Statistics and Data Science. Students choosing this concentration may not pursue an additional minor in Statistics in the Dietrich College of Humanities and Social Sciences.

The requirements for the Statistics concentration are:

### Mathematical Sciences Courses (required)

The alternative courses 21-242, 21-261, and 21-268 (or 21-269) are particularly recommended for a student planning to pursue graduate work.

Courses		Units
21-120	Differential and Integral Calculus	10
21-122	Integration and Approximation	10
21-127	Concepts of Mathematics	12
or 21-128	Mathematical Concepts and Proofs	
21-201	Undergraduate Colloquium	1
21-228	Discrete Mathematics	9-12
or 15-251	Great Ideas in Theoretical Computer Science	
21-241	Matrices and Linear Transformations	11
or 21-242	Matrix Theory	
21-259	Calculus in Three Dimensions	10-12
or 21-266	Vector Calculus using Matrix Algebra	
or 21-268	Multidimensional Calculus	
or 21-269	Vector Analysis	
21-260	Differential Equations	9-10
or 21-261	Introduction to Ordinary Differential Equations	
or 33-231	Physical Analysis	
21-292	Operations Research I	9
21-369	Numerical Methods	12
21-393	Operations Research II	9

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### Statistics Courses (required)

Courses		Units
21-325	Probability	9-12
or 15-259	Probability and Computing	
or 36-218	Probability Theory for Computer Scientists	
36-226	Introduction to Statistical Inference	9
36-401	Modern Regression	9
36-402	Advanced Methods for Data Analysis	9
36-410	Introduction to Probability Modeling	9

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**Economics and Computer Science Courses (required)**

Courses		Units
15-112	Fundamentals of Programming and Computer Science	12
or 02-120	Programming for Scientists	
15-122	Principles of Imperative Computation	12
73-102	Principles of Microeconomics	9
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**Depth Electives (required)**

**Forty-five units** of depth electives, to be chosen from the list below, or any other Mathematical Sciences Elective (at the 21-300 level or above or 21-270 or 21-292). **At least nine of these units must be Mathematical Sciences Electives (21-XXX). At least nine of these units must be Statistics Electives (36-XXX).**

The courses 21-355 and 21-455 are particularly recommended for a student planning to pursue graduate work.

Courses		Units
10-301	Introduction to Machine Learning	12
or 10-315	Introduction to Machine Learning (SCS Majors)	
15-150	Principles of Functional Programming	12
15-210	Parallel and Sequential Data Structures and Algorithms	12
21-270	Introduction to Mathematical Finance	9
21-321	Interactive Theorem Proving	9
21-326	Markov Chains: Theory, Simulation and Applications	9
21-341	Linear Algebra	9
21-355	Principles of Real Analysis I	9-12
or 21-455	Intermediate Real Analysis I	
21-356	Principles of Real Analysis II	9-10
or 21-456	Intermediate Real Analysis II	
21-370	Discrete Time Finance	9
21-373	Algebraic Structures	9
21-378	Mathematics of Fixed Income Markets	9
21-420	Continuous-Time Finance	9
21-484	Graph Theory	9
36-46X	Special Topics (Statistics)	9-12
36-47X	Special Topics (Statistics)	9-12

**MCS General Education (required)**

MCS humanities, social sciences, and science core (114 units)

Note that 73-102 satisfies a requirement from the MCS core.

Minimum number of units required for degree: 360

**B.S. in Mathematical Sciences (Discrete Mathematics and Logic)**

Discrete mathematics is the study of finite and countable structures and algorithms for the manipulation and analysis of such structures, while mathematical logic is the study of axiomatic systems and their mathematical applications. Both are flourishing research areas and have close ties with computer science.

The Discrete Mathematics and Logic concentration provides a rigorous background in discrete mathematics and mathematical logic, together with the elements of theoretical computer science. It prepares the student to pursue research in these fields, or to apply their ideas in the many disciplines (ranging from philosophy to hardware verification) where such ideas have proved relevant.

The requirements for the Discrete Mathematics and Logic concentration are:

**Mathematical Sciences and Computer Science Courses (required)**

The alternative course 21-242 is particularly recommended for a student planning to pursue graduate work. Students who plan to pursue graduate study in mathematical logic are strongly advised to take 21-300.

Courses		Units
15-122	Principles of Imperative Computation	12
15-150	Principles of Functional Programming	12
15-210	Parallel and Sequential Data Structures and Algorithms	12
21-120	Differential and Integral Calculus	10
21-122	Integration and Approximation	10
21-127	Concepts of Mathematics	12
or 21-128	Mathematical Concepts and Proofs	
21-201	Undergraduate Colloquium	1
21-228	Discrete Mathematics	9
or 21-301	Combinatorics	
21-241	Matrices and Linear Transformations	11
or 21-242	Matrix Theory	
21-300	Basic Logic	9
21-341	Linear Algebra	9
21-355	Principles of Real Analysis I	9-12
or 21-455	Intermediate Real Analysis I	
21-373	Algebraic Structures	9

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**Computer Science Electives (required)**

Any two courses at the 300 level or above. The following are specifically suggested:

15-312	Foundations of Programming Languages	12
15-317	Constructive Logic	9
15-451	Algorithm Design and Analysis	12

Students pursuing this concentration who minor in Computer Science must take at least 18 units of 15-300 level (or above) courses to avoid excessive double-counting.

**Depth Electives (required)**

**Seventy-two units** of depth electives, to be chosen from the two lists below, or any other Mathematical Sciences Elective (at the 21-300 level or above or 21-270 or 21-292). **At least thirty-six of these units must be Discrete Mathematics and Logic Electives (List 1).**

## List 1 (Discrete Mathematics and Logic Electives)

Courses		Units
15-251	Great Ideas in Theoretical Computer Science	12
or 21-301	Combinatorics	
21-321	Interactive Theorem Proving	9
21-322	Topics in Formal Mathematics	9
21-325	Probability	9
or 15-259	Probability and Computing	
21-329	Set Theory	9
21-374	Field Theory	9
21-400	Intermediate Logic	9
21-441	Number Theory	9
21-484	Graph Theory	9
21-602	Introduction to Set Theory I	12
21-603	Model Theory I	12
21-610	Algebra I	12
21-701	Discrete Mathematics	12
80-305	Game Theory	9
80-311	Undecidability and Incompleteness	9
80-411	Proof Theory	9
80-413	Category Theory	9

## List 2 (Mathematics Electives)

Courses		Units
21-259	Calculus in Three Dimensions	10-12

or 21-266	Vector Calculus using Matrix Algebra	
or 21-268	Multidimensional Calculus	
or 21-269	Vector Analysis	
21-260	Differential Equations	9-10
or 21-261	Introduction to Ordinary Differential Equations	
or 33-231	Physical Analysis	
21-270	Introduction to Mathematical Finance	9
21-292	Operations Research I	9
21-326	Markov Chains: Theory, Simulation and Applications	9
21-356	Principles of Real Analysis II	9-10
or 21-456	Intermediate Real Analysis II	
21-366	Topics in Applied Mathematics	9
21-369	Numerical Methods	12
21-370	Discrete Time Finance	9
21-371	Functions of a Complex Variable	9
21-393	Operations Research II	9
21-420	Continuous-Time Finance	9
21-410	Research Topics in Mathematical Sciences	9

### MCS General Education (required)

MCS humanities, social sciences, and science core (114 units)

Minimum number of units required for degree: 360

## B.S. in Mathematical Sciences (Computational and Applied Mathematics)

This concentration is designed to prepare students for careers in business or industry which require significant analytical, computational and problem solving skills. It also prepares students with interest in computational and applied mathematics for graduate school.

The students in this concentration develop skills to choose the right framework to quantify or model a problem, analyze it, simulate and in general use appropriate techniques for carrying the effort through to an effective solution. The free electives allow the student to develop an interest in a related area by completing a minor in another department, such as Engineering Studies, Economics, Information Systems or Business Administration.

The requirements for the Computational and Applied Mathematics concentration are:

### Mathematical Sciences Courses (required)

The alternative courses 21-242, 21-261, and 21-268 (or 21-269) are particularly recommended for a student planning to pursue graduate work.

Courses		Units
21-120	Differential and Integral Calculus	10
21-122	Integration and Approximation	10
21-127	Concepts of Mathematics	12
or 21-128	Mathematical Concepts and Proofs	
21-201	Undergraduate Colloquium	1
21-228	Discrete Mathematics	9-12
or 15-251	Great Ideas in Theoretical Computer Science	
21-241	Matrices and Linear Transformations	11
or 21-242	Matrix Theory	
21-259	Calculus in Three Dimensions	10-12
or 21-266	Vector Calculus using Matrix Algebra	
or 21-268	Multidimensional Calculus	
or 21-269	Vector Analysis	
21-260	Differential Equations	9-10
or 21-261	Introduction to Ordinary Differential Equations	
or 33-231	Physical Analysis	
21-325	Probability	9-12
or 15-259	Probability and Computing	
or 36-218	Probability Theory for Computer Scientists	
21-355	Principles of Real Analysis I	9-12
or 21-455	Intermediate Real Analysis I	
21-369	Numerical Methods	12

21-469	Computational Introduction to Partial Differential Equations	12
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### Computer Science Courses (required)

Courses		Units
15-122	Principles of Imperative Computation	12

### Depth Electives (required)

#### Sixty-three total units

- **Twenty-seven of these units** must be Computational and Applied Mathematics (List 1)
- **Twenty-seven of these units** must be Computational and Applied Mathematics Electives (List 1) or Mathematics Electives (List 2) or any other Mathematical Sciences Elective (at the 21-300 level or above or 21-270 or 21-292).
- **Nine units** must be from the two lists below, or Mathematical Sciences (at the 21-300 level or above or 21-270 or 21-292), or Computer Science (at the 15-200 level or above), or Physics (at the 33-300 level or above), or Statistics (must be at the 36-300 level or above and have at least 36-225 as a prerequisite).

#### List 1 (Computational and Applied Mathematics Electives)

Courses		Units
10-301	Introduction to Machine Learning	12
or 10-315	Introduction to Machine Learning (SCS Majors)	
21-270	Introduction to Mathematical Finance	9
21-292	Operations Research I	9
21-326	Markov Chains: Theory, Simulation and Applications	9
21-344	Numerical Linear Algebra	9
21-380	Introduction to Mathematical Modeling	9

#### List 2 (Mathematics Electives)

Courses		Units
21-321	Interactive Theorem Proving	9
21-341	Linear Algebra	9
21-356	Principles of Real Analysis II	9-10
or 21-456	Intermediate Real Analysis II	
21-370	Discrete Time Finance	9
21-371	Functions of a Complex Variable	9
21-373	Algebraic Structures	9
21-378	Mathematics of Fixed Income Markets	9
21-393	Operations Research II	9
21-420	Continuous-Time Finance	9
21-484	Graph Theory	9
21-632	Introduction to Differential Equations	12
21-640	Introduction to Functional Analysis	12
21-651	General Topology	12
21-660	Introduction to Numerical Analysis I	12
21-690	Methods of Optimization	12
21-720	Measure and Integration	12
21-721	Probability	12
21-723	Advanced Real Analysis	12
21-732	Partial Differential Equations I	12

### MCS General Education (required)

MCS humanities, social sciences, and science core (114 units).

Minimum number of units required for degree: 360

## B.A. in Mathematical Sciences

### Mathematical Sciences Courses (required)

21-120	Differential and Integral Calculus	10
21-122	Integration and Approximation	10

21-127	Concepts of Mathematics	12
or 21-128	Mathematical Concepts and Proofs	
21-201	Undergraduate Colloquium	1
21-228	Discrete Mathematics	9-12
or 15-251	Great Ideas in Theoretical Computer Science	
21-241	Matrices and Linear Transformations	11
or 21-242	Matrix Theory	
21-259	Calculus in Three Dimensions	10-12
or 21-266	Vector Calculus using Matrix Algebra	
or 21-268	Multidimensional Calculus	
or 21-269	Vector Analysis	
21-260	Differential Equations	9-10
or 21-261	Introduction to Ordinary Differential Equations	
or 33-231	Physical Analysis	
21-325	Probability	9-12
or 15-259	Probability and Computing	
or 36-218	Probability Theory for Computer Scientists	

### Depth Electives (required)

#### Seventy-two total units

- **Forty-five units** of Mathematical Sciences Electives (at the 21-300 level or above; or 21-270 or 21-292).
- **Twenty-seven units** of Mathematical Sciences (at the 21-300 level or above; or 21-270 or 21-292), or Computer Science (at the 15-200 level or above); or Physics (at the 33-300 level or above); or Statistics (at the 36-300 level or above; and have at least 36-225 as a prerequisite) electives.

### MCS General Education (required)

MCS humanities, social sciences, and science core (114 units)

Minimum number of units required for degree: 360

## Additional Major Requirements

All concentrations within the B.S. in Mathematical Sciences are available as an additional major to students majoring in other departments. The requirements for the additional majors are the same as those for the B.S. degrees, except that the MCS General Education requirements are waived, **along with the requirement to take 21-201**. In order to avoid double-counting issues, students are encouraged to consult with their academic advisor for their primary degree as well as their additional major advisor. Please visit the Department of Mathematical Sciences Undergraduate FAQ website (<https://www.cmu.edu/math/undergrad/faq.html>) (under "Admissions") for further details

## The Minor in Mathematical Sciences

The minor includes six courses. 21-127 Concepts of Mathematics is a prerequisite for 21-228 and recommended for 21-241. The minimum preparation required for 21-355 Principles of Real Analysis I is 21-122 and 21-127 or equivalent courses. Please see below if you are a Computational Finance major.

21-127	Concepts of Mathematics	12
or 21-128	Mathematical Concepts and Proofs	
or 15-151	Mathematical Foundations for Computer Science	
21-228	Discrete Mathematics	9-12
or 15-251	Great Ideas in Theoretical Computer Science	
21-241	Matrices and Linear Transformations	11
or 21-242	Matrix Theory	
21-355	Principles of Real Analysis I	9-12
or 21-455	Intermediate Real Analysis I	
21-xxx	Mathematical Sciences Elective (300-level or higher)	9-12
21-xxx	Mathematical Sciences Elective (300-level or higher)	9-12

To avoid excessive double-counting, the two mathematical sciences electives may not also count toward any other major or minor requirement.

Computational Finance majors who declare a minor in Mathematical Sciences should take the following six courses:

Required courses are:

21-127	Concepts of Mathematics	12
or 21-128	Mathematical Concepts and Proofs	
or 15-151	Mathematical Foundations for Computer Science	
21-228	Discrete Mathematics	9-12
or 15-251	Great Ideas in Theoretical Computer Science	
21-241	Matrices and Linear Transformations	11
or 21-242	Matrix Theory	
21-355	Principles of Real Analysis I	9
21-325	Probability	9-12
or 15-259	Probability and Computing	
or 36-218	Probability Theory for Computer Scientists	

Nine units of Mathematical Sciences Electives, to be chosen from the following list:

21-300	Basic Logic	9
21-301	Combinatorics	9
21-329	Set Theory	9
21-373	Algebraic Structures	9
21-484	Graph Theory	9

\*Students who take 21-325 (or 15-259 or 36-218) to fulfill their BSCF requirements should take an additional 21-3xx elective to avoid excessive double counting.

## The Minor in Discrete Mathematics and Logic

This minor develops the fundamentals of discrete mathematics and logic necessary to understand the mathematical foundations of many computer related disciplines. Required courses are:

21-228	Discrete Mathematics <sup>1</sup>	9
or 21-301	Combinatorics	
21-300	Basic Logic	9

<sup>1</sup>21-127 Concepts of Mathematics is a prerequisite for 21-228.

**Thirty-six units** of Mathematical Sciences Electives, to be chosen from the following two groups (at least nine units from each group).

Logic		
21-321	Interactive Theorem Proving	9
21-329	Set Theory	9
21-400	Intermediate Logic	9
21-602	Introduction to Set Theory I	12
21-603	Model Theory I	12
80-305	Game Theory	9
80-311	Undecidability and Incompleteness	9
80-315	Logics for Knowledge and Belief	9
80-411	Proof Theory	9
80-413	Category Theory	9
Algebra and Discrete Mathematics		
21-341	Linear Algebra	9
21-373	Algebraic Structures	9
21-374	Field Theory	9
21-441	Number Theory	9
21-484	Graph Theory	9
21-610	Algebra I	12
21-701	Discrete Mathematics	12

To avoid excessive double-counting, at least two mathematical sciences electives may not also count toward any other major or minor requirement.

## The Honors Degree Program

This demanding program qualifies the student for an additional degree, the Master of Science in Mathematical Sciences. Admission to the Honors

Degree Program is selective and interested students should apply for admission during their junior year. In the application process, the Department will hold to the same high standards which apply to admission to any graduate program. Applicants are not absolutely required to have taken the Mathematical Studies courses and may be admitted on the basis of exceptionally strong performance in non-honors mathematics courses or of accomplishments in research. Applicants are expected to have completed the Mathematical Studies sequences in algebra and analysis or 21-355/21-356 and 21-373/21-341 prior to application. 21-455/21-456 may be taken in place of 21-355/21-356.

In order to complete the Honors Degree Program, students must complete five mathematics graduate courses with grades of B or better and write an honors thesis. At the time of admission, students will declare a timetable on which they plan to take the graduate courses, do the research required for the thesis, and write up their work: this timetable can naturally be adjusted as required. At most, one of these five graduate courses may be applied towards the student's bachelor's degree program.

At least three graduate courses must come from this list of introductory courses:

- 21-602 Introduction to Set Theory I
- 21-603 Model Theory I
- 21-610 Algebra I
- 21-632 Introduction to Differential Equations
- 21-640 Introduction to Functional Analysis
- 21-651 General Topology
- 21-701 Discrete Mathematics
- 21-720 Measure and Integration
- 21-721 Probability
- 21-737 Probabilistic Combinatorics

By special permission of the department, one graduate course with sufficient mathematical content offered in another department may be counted. The honors thesis may either be research-based or expository: expository theses must be at a high mathematical level, at least that of a second-year graduate course. Students should plan on finding a thesis advisor by the end of their junior year. Students are required to take 21-901 Honors Program M.S. Research during their senior year, subject to the following conditions:

1. Students must pass a minimum of 15 units of 21-901 to earn the M.S. in Mathematical Sciences.
2. Students who have not defended their thesis by the Add-Course-Deadline (<https://www.cmu.edu/hub/calendar/>) during each of their last two semesters must register for a minimum of three units of 21-901 for that semester.
3. Students may not overload more than 66 units while taking 21-901.

The Master of Science in Mathematical Sciences may be earned together with a bachelor of science from another department.

## Faculty

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