MATHEMATICS

Courses offered by the Department of Mathematics are listed under the subject code MATH on the (http://explorecourses.stanford.edu/CourseSearch/search/?view=catalog&catalog=&page=0&q=MATH&filter-catalognumber-MATH=on) Stanford Bulletin's (http://explorecourses.stanford.edu/CourseSearch/search/?view=catalog&catalog=&page=0&q=MATH&filter-catalognumber-MATH=on) ExploreCourses web site (http://explorecourses.stanford.edu/CourseSearch/search/?view=catalog&catalog=&page=0&q=MATH&filter-catalognumber-MATH=on).

The Department of Mathematics offers programs leading to the degrees of Bachelor of Science, Master of Science, and Doctor of Philosophy in Mathematics, and also participates in the program leading to the B.S. in Mathematical and Computational Science, and the M.S. and Ph.D. degree programs offered through the Institute for Computational & Mathematical Engineering.

Mission of the Undergraduate Program in Mathematics

The mission of the undergraduate program in Mathematics is to provide students with a broad understanding of mathematics encompassing logical reasoning, generalization, abstraction, and formal proof. Courses in the program teach students to create, analyze, and interpret mathematical models and to communicate sound arguments based on mathematical reasoning and careful data analysis. The mathematics degree prepares students for careers in the corporate sector, tech industry, government agencies, and for graduate programs in mathematics.

Learning Outcomes (Undergraduate)

The department expects undergraduate majors in the program to be able to demonstrate the following learning outcomes. These learning outcomes are used in evaluating students and the department's undergraduate program. Students are expected to demonstrate:

1. problem solving skills,
2. the ability to formulate proofs and to structure mathematical arguments,
3. the ability to communicate mathematical ideas via extended written presentation.

Advanced Placement in Mathematics

Students can receive units of advanced placement credit for single-variable calculus, depending on their scores on the CEEB Advanced Placement Examination or the IB Exam. See the the "Advanced Placement (http://exploredegrees.stanford.edu/undergraduatedegreesandprograms/#aptext)" section of this bulletin.

Those who have not studied single-variable calculus or have studied it partially but are not ready to begin with multivariable calculus (MATH 50-series) should begin at the single-variable course recommended by the math placement diagnostic.

Students who are ready to study multivariable calculus (based on prior courseswork or exams, or recommended by the math placement diagnostic) should begin with one of the following courses:

		Units
MATH 51	Linear Algebra, Multivariable Calculus, and Modern Applications	5
MATH 52	Integral Calculus of Several Variables	5
MATH 53	Ordinary Differential Equations with Linear Algebra	5

The above sequence supplies the necessary mathematics background for most majors in science and engineering. It also provides a solid foundation for the major or minor in Mathematics, or in Mathematical and Computational Science.

Bachelor of Science in Mathematical and Computational Science

The Department of Mathematics participates with the departments of Computer Science, Management Science and Engineering, and Statistics in a program leading to a B.S. in Mathematical and Computational Science. See the "Mathematical and Computational Science (http://exploredegrees.stanford.edu/schoolofhumanitiesandsciences/mathematicalandcomputationalscience/)" section of this bulletin.

Introductory and Undergraduate Courses

The department offers a year-long sequence in single-variable calculus: MATH 19, MATH 20, and MATH 21.

There are three options for studying multivariable mathematics:

1. MATH 51, MATH 52, and MATH 53 cover differential and integral calculus in several variables, linear algebra, and ordinary differential equations. These topics are taught in an integrated fashion and emphasize applications. MATH 51 covers differential calculus in several variables and introduces matrix theory and basic linear algebra; MATH 52 covers integral calculus in several variables and vector analysis; MATH 53 studies further topics in linear algebra and applies them to ordinary differential equations. This sequence is strongly recommended for incoming freshmen who have mastered single-variable calculus.
2. The sequence MATH 61CM, MATH 62CM, and MATH 63CM (Modern Mathematics: Continuous Methods) covers the material of the Math 50 series at a much more advanced level with an emphasis on rigorous proofs and conceptual arguments.
3. The sequence MATH 61DM, MATH 62DM, and MATH 63DM (Modern Mathematics: Discrete Methods) covers the same linear algebra material as the Math 60CM series and otherwise focuses on topics in discrete mathematics, algebra, and probability theory at an advanced level with an emphasis on rigorous proofs.

Learning Outcomes (Graduate)

The master's degree is conferred upon candidates who have developed advanced knowledge and skills in Mathematics. This is achieved through completion of courses, in the primary field as well as related areas, and experience with independent work and specialization.

The Ph.D. is conferred upon candidates who have demonstrated substantial scholarship and the ability to conduct independent research and analysis in Mathematics. Through completion of advanced course work and rigorous skills training, the doctoral program prepares students to make original contributions to the knowledge of Mathematics and to interpret and present the results of such research.

Bachelor of Science in Mathematics

The following department requirements are in addition to the University's basic requirements for the bachelor's degree.

Students wishing to major in Mathematics must satisfy the following requirements and complete a minimum of 64 units:

1. Department of Mathematics courses totaling at least 49 units credit; among these at least eight courses worth at least 3 units each numbered above 63. Such courses must be taken for a letter grade. For the purposes of this requirement, STATS 116 Theory of Probability, PHIL 151 Metalogic, and PHIL 152 Computability and Logic count as Department of Mathematics courses.
2. Additional units taken from Department of Mathematics courses numbered 101 and above or from approved courses in other disciplines with significant mathematical content, totaling at least 15 units credit. At least 9 of these units must be taken for a letter grade.
3. The Department of Mathematics adviser can be any member of the department's faculty.
4. To receive the department's recommendation for graduation, a student must have been enrolled as a major in the Department of Mathematics for a minimum of two full quarters, including the quarter immediately before graduation.

Students with an Advanced Placement score of 5 in BC math may receive 10 units credit and fulfill requirement '1' by taking at least 39 units of Department of Mathematics courses. Students with an Advanced Placement score of at least 4 in BC math or 5 in AB math may receive 8 units credit and fulfill requirement '1' by taking at least 41 units of Department of Mathematics courses.

Freshman and sophomore introductory seminar courses may be counted among the choice of courses under item '1'. Other variations of the course requirements laid down above (under items '1' and '2') may, in some circumstances, be allowed. For example, students transferring from other universities may be allowed credit for some courses completed before their arrival at Stanford. However, at least 24 units of the 49 units under item '1' above and 9 of the units under item '2' above must be taken at Stanford. In all cases, approval for variations in the degree requirements must be obtained from the department's Director of Undergraduate Studies. The policy of the Mathematics Department is that no courses other than the MATH 60 series and below may be double-counted toward any other University major or minor.

Proof Writing

For students who are not experienced with writing mathematical proofs, this crucial skill can be learned by taking any one of the following courses: MATH 110 Applied Number Theory and Field Theory, MATH 113 Linear Algebra and Matrix Theory, or MATH 115 Functions of a Real Variable (after finishing the chosen calculus sequence).

Preparation for Graduate School:

It is to be emphasized that the above regulations are minimum requirements for the major; students contemplating graduate work in mathematics are strongly encouraged to include the courses MATH 116 Complex Analysis, MATH 120 Groups and Rings, MATH 121 Galois Theory, MATH 147 Differential Topology or MATH 148 Algebraic Topology, and MATH 171 Fundamental Concepts of Analysis in their selection of courses, and in addition, take at least three Department of Mathematics courses over and above the minimum requirements laid out under items '1' and '2' above, including at least one 200-level course. Such students are also encouraged to consider the possibility of taking the honors program.

Sample Course Plans

To help develop a sense of the type of course selection (under items '1' and '2' above) that would be recommended for math majors with various backgrounds and interests, see the following examples. These represent only a few of a very large number of possible combinations of courses that could be taken in fulfillment of the Mathematics major requirements:

Example 1: for students with both pure and applied interests

		Units
Single-variable calculus: AP Credit, (MATH 19, MATH 20, MATH 21)		8-10
Multivariable calculus: (MATH 51, MATH 52, MATH 53)		15
MATH 104	Applied Matrix Theory	3
or MATH 113	Linear Algebra and Matrix Theory	
MATH 106	Functions of a Complex Variable	3
MATH 109	Applied Group Theory	3
MATH 110	Applied Number Theory and Field Theory	3
MATH 115	Functions of a Real Variable	3
Plus any selection of at least eight of the following courses, including three Department of Mathematics courses:		26
MATH 107	Graph Theory	
MATH 108	Introduction to Combinatorics and Its Applications	
MATH 131P	Partial Differential Equations	
MATH 143	Differential Geometry	
MATH 144	Introduction to Topology and Geometry	
MATH 147	Differential Topology	
MATH 148	Algebraic Topology	
MATH 152	Elementary Theory of Numbers	
MATH 161	Set Theory	
CME 108	Introduction to Scientific Computing	
ECON 50	Economic Analysis I	
PHYSICS 41	Mechanics	
PHYSICS 43	Electricity and Magnetism	
PHYSICS 45	Light and Heat	
STATS 116	Theory of Probability	
or MATH 151	Introduction to Probability Theory	
Total Units		64-66

The courses from other departments are only meant as examples; there are many suitable courses in several departments that can be taken to fulfill part or all of requirement '2'.

Example 2: for students with strong theoretical interest and considering graduate school in math

		Units
Single-variable calculus: AP Credit, (MATH 19, MATH 20, MATH 21)		8-10
Select one of the following multivariable calculus sequences:		15
Math 50 Series: (MATH 51, MATH 52, MATH 53). These courses are not proof-oriented.		
Math 60CM Series: (MATH 61CM, MATH 62CM, MATH 63CM). This proof-oriented sequence is called Modern Mathematics: Continuous Methods		
Math 60DM Series: (MATH 61DM, MATH 62DM, MATH 63DM). This proof-oriented sequence is called Modern Mathematics: Discrete Methods		
MATH 101	Math Discovery Lab	3
MATH 106	Functions of a Complex Variable	3
or MATH 116	Complex Analysis	
MATH 113	Linear Algebra and Matrix Theory	3
MATH 120	Groups and Rings	3
MATH 171	Fundamental Concepts of Analysis	3

Plus 24-26 units of math courses numbered 121 or higher (the logic courses PHIL 151 and PHIL 152 are considered to be such courses), including at least one algebra course, one analysis course, and one geometry/topology course. (See the description of the honors program below)		26
Total Units		64-66

In addition, those contemplating eventual graduate work in Mathematics should consider including at least one graduate-level math course such as MATH 205A Real Analysis, MATH 210A Modern Algebra I, or MATH 215A Algebraic Topology or MATH 215B Differential Topology. Such students should also consider the possibility of entering the honors program.

Example 3: for students interested in applied math

Students desiring significant computational and/or financial and/or statistical components are encouraged to also consider the Mathematics and Computational Science program.

		Units
Single-variable calculus: AP Credit, (MATH 19, MATH 20, MATH 21)		8-10
Select one of the following multivariable calculus sequences:		15
Math 50 Series (MATH 51, MATH 52, MATH 53). These courses are not proof-oriented.		
Math 60 Series (MATH 61DM, MATH 62DM, MATH 63DM). This proof-oriented sequence is called Modern Mathematics: Discrete Methods		
MATH 104	Applied Matrix Theory	3
MATH 106	Functions of a Complex Variable	3
MATH 107	Graph Theory	3
MATH 108	Introduction to Combinatorics and Its Applications	3
MATH 109	Applied Group Theory	3
MATH 110	Applied Number Theory and Field Theory	3
MATH 115	Functions of a Real Variable	3
MATH 131P	Partial Differential Equations	3
STATS 116	Theory of Probability	3
or MATH 151	Introduction to Probability Theory	
Plus at least 12 units of additional courses in applied mathematics, including, for example, suitable courses from the departments of Physics, Computer Science, Economics, Engineering, and Statistics.		14
Total Units		64-66

Honors Program

This option is intended for students who have strong theoretical interests and abilities in mathematics. The goal is to give students a thorough introduction to the main branches of mathematics. The honors program requires a senior thesis, which can involve either original research or expository work on advanced topics in mathematics. This option provides an excellent background with which to enter a Master's or Ph.D. program in Mathematics. Students completing the honors program are awarded a B.S. in Mathematics with Honors.

It is recommended that either sequence (MATH 61CM, MATH 62CM, MATH 63CM) or (MATH 61DM, MATH 62DM, MATH 63DM) be taken in the freshman year. To graduate with a B.S. in Mathematics with Honors, the following conditions apply in addition to the usual requirements for math majors:

1. The selection of courses under items '1' and '2' above must contain:

		Units
MATH 116	Complex Analysis	3
MATH 120	Groups and Rings	3
MATH 171	Fundamental Concepts of Analysis	3

   And must also include seven additional 3-unit Math courses numbered 121 or higher. (The logic courses PHIL 151 Metalogic and PHIL 152 Computability and Logic can also be used.) These seven courses must include at least:

		Units
One Algebra Course:		
MATH 121	Galois Theory	3
MATH 122	Modules and Group Representations	3
MATH 152	Elementary Theory of Numbers	3
MATH 154	Algebraic Number Theory	3
One Analysis Course:		
MATH 136	Stochastic Processes	3
MATH 151	Introduction to Probability Theory	3
MATH 155	Analytic Number Theory	3
MATH 172	Lebesgue Integration and Fourier Analysis	3
MATH 173	Theory of Partial Differential Equations	3
MATH 175	Elementary Functional Analysis	3
One Geometry/Topology Course:		
MATH 143	Differential Geometry	3
MATH 144	Introduction to Topology and Geometry	3
MATH 145	Algebraic Geometry	3
MATH 147	Differential Topology	3
MATH 148	Algebraic Topology	3

2. All courses counting towards the honors requirements (MATH 116, MATH 120, MATH 171, all 7 additional Math courses used to fulfill the major requirement, and MATH 197) must be taken for a letter grade.
3. Students must have an average GPA of at least a 3.3 across all math classes counting towards the major at the time of applying for honors to be eligible for acceptance into the honors program, as well as upon graduation to graduate with honors.
4. Majors interested in honors can apply in winter quarter of their junior year at the earliest, and no later than the last day of classes in the spring quarter of junior year.
5. Students in the honors program must write a senior thesis. In order to facilitate this, the student must, by the end of the junior year, choose an undergraduate thesis adviser from the Department of Mathematics faculty and map out a concentrated reading program under the direction and guidance of the adviser. This will occur when the student applies for honors. During the senior year, the student must enroll in MATH 197 Senior Honors Thesis with his/her adviser for a total of 6 units (recommended to be spread over three quarters), and work toward completion of the thesis under the direction and guidance of the thesis adviser. The thesis may contain original material, or be a synthesis of work in current or recent research literature. The 6 units of credit for MATH 197 Senior Honors Thesis are required in addition to the 64 units required of the major. (See the major requirements at the top of the page.)
6. The deadline for the senior thesis final draft is the Monday of week 8 of the student's graduation quarter.

In addition to the minimum requirements laid out above, it is strongly recommended that students take at least one graduate-level course (that is, at least one course in the 200 plus range). MATH 205A Real Analysis, MATH 210A Modern Algebra I, and MATH 215A Algebraic Topology or MATH 215B Differential Topology are especially recommended in this context.

Students with questions about the honors program should see the department's director of undergraduate studies.

Computer Science Theory/Discrete Mathematics Subplan

There are two pathways to achieve a Mathematics B.S. degree:

- The Mathematics bachelor's degree, or
- The Mathematics bachelor's degree with the Computer Science Theory/Discrete Mathematics subplan.

The following requirements refer to the Mathematics Bachelor's degree with the Computer Science Theory/Discrete Mathematics Subplan. Students who are interested in the Mathematics Bachelor's degree should see the Bachelor's tab (p. 1).

The Computer Science Theory/Discrete Mathematics subplan is declared on Axess; it appears on the transcript and the diploma.

Computer Science Theory/Discrete Mathematics Subplan Description

This subplan is intended for students wishing for a strong and deep background in the area of computer science theory and mathematics. The subplan could prepare students for graduate work in either area, as well as for other careers requiring particular strength in this type of thinking. The emphasis of this subplan is on theory. Students interested in a combination of mathematics and computer science more generally should consider the Bachelor of Science in Mathematical and Computational Science. Depending on their interests, students are also encouraged to consider the regular Mathematics major, the Computer Science major, and in particular, the Computer Science Theory track of the Computer Science major.

Course Requirements

The subplan requires a minimum of 64 units as outlined in requirements 1 and 2 of the Bachelor of Science in Mathematics; see the Bachelor's tab (p. 1). The selection of courses for the 64 total units must contain the required courses listed in the chart below. For the purposes of the subplan, the required Computer Science Department courses can count toward either the 49 units of Math Department courses or the 15 additional units. All required courses must be taken for a letter grade. It is highly recommended to complete the MATH 60DM sequence, although it is not required.

		Units
Required Courses		
Required Math Courses		
MATH 106	Functions of a Complex Variable	3
or MATH 116	Complex Analysis	
MATH 120	Groups and Rings	3
MATH 171	Fundamental Concepts of Analysis	3
Required CS Theory Courses		
CS 154	Introduction to the Theory of Computation	3-4
CS 161	Design and Analysis of Algorithms	3-5
Additional Math Courses		
Two of the following:		6-8
MATH 61DM	Modern Mathematics: Discrete Methods	
MATH 107	Graph Theory	
MATH 108	Introduction to Combinatorics and Its Applications	
One of the following:		3-5
MATH 151	Introduction to Probability Theory	
MATH 230A	Theory of Probability I	
STATS 116	Theory of Probability	
Two of the following:		6
MATH 113	Linear Algebra and Matrix Theory	
MATH 152	Elementary Theory of Numbers	
MATH 154	Algebraic Number Theory	
MATH 155	Analytic Number Theory	
MATH 159	Discrete Probabilistic Methods	
MATH 161	Set Theory	
Additional CS Theory Courses:		
Four of the following:		12-13
CS 167		
CS 168	The Modern Algorithmic Toolbox	
CS 254	Computational Complexity	
CS 255	Introduction to Cryptography	
CS 261	Optimization and Algorithmic Paradigms	
CS 265	Randomized Algorithms and Probabilistic Analysis	
CS 268	Geometric Algorithms	
Total Units		42-50

Minor in Mathematics

To qualify for the minor in Mathematics, a student should complete, for a letter grade, at least six Department of Mathematics courses numbered 51 or higher, totaling a minimum of 24 units. For the purposes of this requirement, STATS 116 Theory of Probability, PHIL 151 Metalogic, and PHIL 152 Computability and Logic count as Department of Mathematics courses. No other courses from outside the Department of Mathematics may be used towards the minor in Mathematics.

It is recommended that these courses include:

		Units
Math Minor		
MATH 51	Linear Algebra, Multivariable Calculus, and Modern Applications	5
or MATH 61CM	Modern Mathematics: Continuous Methods	
or MATH 61DM	Modern Mathematics: Discrete Methods	
MATH 52	Integral Calculus of Several Variables	5
or MATH 62CM	Modern Mathematics: Continuous Methods	
or MATH 62DM	Modern Mathematics: Discrete Methods	
MATH 53	Ordinary Differential Equations with Linear Algebra	5
or MATH 63CM	Modern Mathematics: Continuous Methods	
or MATH 63DM	Modern Mathematics: Discrete Methods	
Plus three additional MATH courses		9
Total Units		24

At least 12 of the units applied toward the minor in Mathematics must be taken at Stanford. The policy of the Mathematics Department is that no courses other than the MATH 50/60 series and below may be double-counted toward any other University major or minor.

Master of Science in Mathematics

The University's basic requirements for the master's degree are discussed in the "Graduate Degrees (http://exploredegrees.stanford.edu/graduatedegrees/)" section of this bulletin. Students should pay particular attention to the University's course requirements for graduate degrees.

University Coterminal Requirements

Coterminal master's degree candidates are expected to complete all master's degree requirements as described in this bulletin. University requirements for the coterminal master's degree are described in the "Coterminal Master's Program (http://exploredegrees.stanford.edu/cotermdegrees/)" section. University requirements for the master's degree are described in the "Graduate Degrees (http://exploredegrees.stanford.edu/graduatedegrees/#masterstext)" section of this bulletin.

After accepting admission to this coterminal master's degree program, students may request transfer of courses from the undergraduate to the graduate career to satisfy requirements for the master's degree. Transfer of courses to the graduate career requires review and approval of both the undergraduate and graduate programs on a case by case basis.

In this master's program, courses taken three quarters prior to the first graduate quarter, or later, are eligible for consideration for transfer to the graduate career. No courses taken prior to the first quarter of the sophomore year may be used to meet master's degree requirements.

Course transfers are not possible after the bachelor's degree has been conferred.

The University requires that the graduate advisor be assigned in the student's first graduate quarter even though the undergraduate career may still be open. The University also requires that the Master's Degree Program Proposal be completed by the student and approved by the department by the end of the student's first graduate quarter.

The following are specific departmental requirements:

Candidates must complete an approved course program of 45 units of courses beyond the department requirements for the B.S. degree, of which at least 36 units must be Mathematics Department courses, taken for a letter grade. The Mathematics Department courses must include at least 18 units numbered 200 or above. The candidate must have a grade point average (GPA) of 3.0 (B) over all course work taken in Mathematics, and a GPA of 3.0 (B) in the 200-level courses considered separately. Course work for the M.S. degree must be approved during the first quarter of enrollment in the program by the department's Director of Graduate Studies.

The Financial Mathematics M.S. degree program is no longer offered through the School of Humanities and Sciences. The Institute for Computational and Mathematical Engineering (ICME (https://icme.stanford.edu/)) now offers a master's degree track in Mathematical and Computational Finance (http://exploredegrees.stanford.edu/schoolofengineering/instituteforcomputationalandmathematicalengineering/#masterstext).

Doctor of Philosophy in Mathematics

The University's basic requirements for the doctorate (residence, dissertation, examinations, etc.) are discussed in the "Graduate Degrees (http://exploredegrees.stanford.edu/graduatedegrees/)" section of this bulletin. The following are specific departmental requirements.

To be admitted to candidacy, the student must have successfully completed 27 units of graduate courses (that is, courses numbered 200 and above). In addition, the student must pass qualifying examinations given by the department.

Beyond the requirements for candidacy, the student must complete a course of study approved by the Graduate Affairs Committee of the Department of Mathematics and submit an acceptable dissertation. In accordance with University requirements, Ph.D. students must complete a total of 135 course units beyond the bachelor's degree. These courses should be Department of Mathematics courses or approved courses from other departments. The course program should display substantial breadth in mathematics outside the student's field of application. The student must receive a grade point average (GPA) of 3.0 (B) or better in courses used to satisfy the Ph.D. requirement. In addition, the student must pass the Department area examination and the University oral examination.

Experience in teaching is emphasized in the Ph.D. program. Each student is required to complete nine quarters of such experience. The nature of the teaching assignment for each of those quarters is determined by the department in consultation with the student. Typical assignments include teaching or assisting in teaching an undergraduate course or lecturing in an advanced seminar.

For further information concerning degree programs, fellowships, and assistantships, inquire of the department's student services office.

Ph.D. Minor in Mathematics

Requirements for the Ph.D. Minor in Mathematics are:

		Units
Complete both of the following Sequences: [1, 2]		
Sequence 1		
MATH 106	Functions of a Complex Variable	3
or MATH 116	Complex Analysis	
MATH 131P	Partial Differential Equations	3
Sequence 2		
MATH 113	Linear Algebra and Matrix Theory	3
MATH 120	Groups and Rings	3
or MATH 152	Elementary Theory of Numbers	
Additional Courses		
21 units of 200-level MATH courses [3]		21
Total Units		33

1 The 100-level courses may have been completed during undergraduate study, and their equivalents from other universities are acceptable.

2 A third coherent sequence designed by the student, subject to the approval of the graduate committee, may be considered as a substitute for Sequence 1 or 2.

3 The 200-level courses must be taken at Stanford and approved by the Department of Mathematics Ph.D. minor adviser.

COVID-19 Policies

On July 30, the Academic Senate adopted grading policies effective for all undergraduate and graduate programs, excepting the professional Graduate School of Business, School of Law, and the School of Medicine M.D. Program. For a complete list of those and other academic policies relating to the pandemic, see the "COVID-19 and Academic Continuity (http://exploredegrees.stanford.edu/covid-19-policy-changes/#tempdepttemplatetabtext)" section of this bulletin.

The Senate decided that all undergraduate and graduate courses offered for a letter grade must also offer students the option of taking the course for a "credit" or "no credit" grade and recommended that deans, departments, and programs consider adopting local policies to count courses taken for a "credit" or "satisfactory" grade toward the fulfillment of degree-program requirements and/or alter program requirements as appropriate.

Undergraduate Degree Requirements

Grading

Math courses taken during Spring 2020 or during the 2020-21 academic year that ordinarily count toward the Math major will still be valid if taken S/NC (Spring 2020) or CR/NC (2020-21). These will not count against the limit of 6 CR/NC elective units that may be applied towards the major.

Graduate Degree Requirements

Grading

The Mathematics Department has not changed its policy concerning 'CR' (credit) or 'S' (satisfactory) grades in degree requirements requiring a letter grade for academic year 2020-21.

Graduate Advising Expectations

The Department of Mathematics is committed to providing academic advising in support of graduate student scholarly and professional development. When most effective, this advising relationship entails collaborative and sustained engagement by both the adviser and the advisee. As a best practice, advising expectations should be periodically discussed and reviewed to ensure mutual understanding. Both the adviser and the advisee are expected to maintain professionalism and integrity.

Faculty advisers guide students in key areas such as selecting courses, designing and conducting research, developing of teaching pedagogy, navigating policies and degree requirements, and exploring academic opportunities and professional pathways.

Graduate students are active contributors to the advising relationship, proactively seeking academic and professional guidance and taking responsibility for informing themselves of policies and degree requirements for their graduate program.

For a statement of University policy on graduate advising, see the "Graduate Advising (http://exploredegrees.stanford.edu/graduatedegrees/#advisingandcredentialstext)" section of this bulletin.

Emeriti: Gregory Brumfiel, Gunnar Carlsson, Robert Finn, Yitzhak Katznelson, Harold Levine, Jun Li, Tai-Ping Liu, R. James Milgram, Donald Ornstein, Richard Schoen, Leon Simon, Ralph L. Cohen

Chair: Rafe Mazzeo

Director of Graduate Studies: Jan Vondrák

Director of Undergraduate Studies: Brian Conrad

Professors: Daniel Bump, Emmanuel Candès, Sourav Chatterjee, Brian Conrad, Amir Dembo (on leave Spring 2021), Persi Diaconis, Yakov Eliashberg, Jacob Fox, June Huh, Steven Kerckhoff (on leave Winter 2021), Eugenia Malinnikova, Ciprian Manlescu, Rafe Mazzeo, Eleny Ionel, George Papanicolaou (on leave Spring 2021), Lenya Ryzhik, Kannan Soundararajan, Richard Taylor (on leave Spring 2021), Ravi Vakil, András Vasy, Brian White (on leave Spring 2021), Lexing Ying

Professor (Teaching): Tadashi Tokieda

Associate Professor: Jan Vondrák, Jonathan Luk

Assistant Professors: Otis Chodosh

Courtesy Professors: Moses Charikar, Renata Kallosh, Andrea Montanari

Adjunct Professors: Brian Conrey, David Hoffman

Szegö Assistant Professors: Perry Kleinhenz, Matthew Kwan, Joonhyun La, Zhenkun Li, Chao Ma, Hunter Spink, Steve Trettel, Umut Varolgunes, Sara Venkatesh

Senior Lecturer: Mark Lucianovic

Lecturers: Pawel Grzegrzolka, Gene Kim, Christine Taylor, Wojciech Wieczorek

Courses

MATH 19. Calculus. 3 Units.
Introduction to differential calculus of functions of one variable. Review of elementary functions (including exponentials and logarithms), limits, rates of change, the derivative and its properties, applications of the derivative. Prerequisites: trigonometry, advanced algebra, and analysis of elementary functions (including exponentials and logarithms). You must have taken the math placement diagnostic (offered through the Math Department website) in order to register for this course.

MATH 19A. Calculus, ACE. 1 Unit.
Additional problem solving session for Math 19 guided by a course assistant. Concurrent enrollment in Math 19 required. Application required: https://engineering.stanford.edu/students-academics/equity-and-inclusion-initiatives/undergraduate-programs/additional-calculus.

MATH 20. Calculus. 3 Units.
The definite integral, Riemann sums, antiderivatives, the Fundamental Theorem of Calculus. Integration by substitution and by parts. Area between curves, and volume by slices, washers, and shells. Initial-value problems, exponential and logistic models, direction fields, and parametric curves. Prerequisite: Math 19 or equivalent. If you have not previously taken a calculus course at Stanford then you must have taken the math placement diagnostic (offered through the Math Department website) in order to register for this course.

MATH 20A. Calculus, ACE. 1 Unit.
Additional problem solving session for Math 20 guided by a course assistant. Concurrent enrollment in Math 20 required. Application required: https://engineering.stanford.edu/students-academics/equity-and-inclusion-initiatives/undergraduate-programs/additional-calculus.

MATH 21. Calculus. 4 Units.
This course addresses a variety of topics centered around the theme of "calculus with infinite processes", largely the content of BC-level AP Calculus that isn't in the AB-level syllabus. It is needed throughout probability and statistics at all levels, as well as to understand approximation procedures that arise in all quantitative fields (including economics and computer graphics). After an initial review of limit rules, the course goes on to discuss sequences of numbers and of functions, as well as limits "at infinity" for each (needed for any sensible discussion of long-term behavior of a numerical process, such as: iterative procedures and complexity in computer science, dynamic models throughout economics, and repeated trials with data in any field). Integration is discussed for rational functions (a loose end from Math 20) and especially (improper) integrals for unbounded functions and "to infinity": this shows up in contexts as diverse as escape velocity for a rocket, the present value of a perpetual yield asset, and important calculations in probability (including the famous "bell curve" and to understand why many statistical tests work as they do). The course then turns to infinite series (how to "sum" an infinite collection of numbers), some useful convergence and divergence rests for these, and the associated killer app: power series and their properties, as well as Taylor approximations, all of which provide the framework that underlies virtually all mathematical models used in any quantitative field.

MATH 21A. Calculus, ACE. 5 Units.
Students attend one of the regular MATH 21 lectures with a longer discussion section of two hours per week instead of one. Active mode: students in small groups discuss and work on problems, with a TA providing guidance and answering questions. Application required: https://forms.gle/BZJqJTawa5PUqe9E7.

MATH 51. Linear Algebra, Multivariable Calculus, and Modern Applications. 5 Units.
This course provides unified coverage of linear algebra and multivariable differential calculus, and the free course e-text connects the material to many fields. Linear algebra in large dimensions underlies the scientific, data-driven, and computational tasks of the 21st century. The linear algebra portion includes orthogonality, linear independence, matrix algebra, and eigenvalues with applications such as least squares, linear regression, and Markov chains (relevant to population dynamics, molecular chemistry, and PageRank); the singular value decomposition (essential in image compression, topic modeling, and data-intensive work in many fields) is introduced in the final chapter of the e-text. The multivariable calculus portion includes unconstrained optimization via gradients and Hessians (used for energy minimization), constrained optimization (via Lagrange multipliers, crucial in economics), gradient descent and the multivariable Chain Rule (which underlie many machine learning algorithms, such as backpropagation), and Newton's method (an ingredient in GPS and robotics). The course emphasizes computations alongside an intuitive understanding of key ideas. The widespread use of computers makes it important for users of math to understand concepts: novel users of quantitative tools in the future will be those who understand ideas and how they fit with examples and applications. This is the only course at Stanford whose syllabus includes nearly all the math background for CS 229, which is why CS 229 and CS 230 specifically recommend it (or other courses resting on it). For frequently asked questions about the differences between Math 51 and CME 100, see the FAQ on the placement page on the Math Department website. Prerequisite: Math 21 or the math placement diagnostic (offered through the Math Department website) in order to register for this course.

MATH 51A. Linear Algebra, Multivariable Calculus, and Modern Applications, ACE. 6 Units.
Students attend one of the regular MATH 51 lectures with a longer discussion section of four hours per week instead of two. Active mode: students in small groups discuss and work on problems from a worksheet distributed 2 or 3 days in advance, with a TA providing guidance and answering questions. Application required: https://forms.gle/7Bexo81r9YcZYRW1A.

MATH 52. Integral Calculus of Several Variables. 5 Units.
Iterated integrals, line and surface integrals, vector analysis with applications to vector potentials and conservative vector fields, physical interpretations. Divergence theorem and the theorems of Green, Gauss, and Stokes. Prerequisite: Math 21 and Math 51 or equivalents.

MATH 52A. Integral Calculus of Several Variables, ACE. 1 Unit.
Additional problem solving session for Math 52 guided by a course assistant. Concurrent enrollment in Math 52 required. Application required: https://engineering.stanford.edu/students-academics/equity-and-inclusion-initiatives/undergraduate-programs/additional-calculus.

MATH 53. Ordinary Differential Equations with Linear Algebra. 5 Units.
Ordinary differential equations and initial value problems, systems of linear differential equations with constant coefficients, applications of second-order equations to oscillations, matrix exponentials, Laplace transforms, stability of non-linear systems and phase plane analysis, numerical methods. Prerequisite: Math 21 and Math 51 or equivalents.

MATH 53A. Ordinary Differential Equations with Linear Algebra, ACE. 1 Unit.
Additional problem solving session for Math 53 guided by a course assistant. Concurrent enrollment in Math 53 required. Application required: https://engineering.stanford.edu/students-academics/equity-and-inclusion-initiatives/undergraduate-programs/additional-calculus.

MATH 56. Proofs and Modern Mathematics. 3 Units.
How do mathematicians think? Why are the mathematical facts learned in school true? In this course students will explore higher-level mathematical thinking and will gain familiarity with a crucial aspect of mathematics: achieving certainty via mathematical proofs, a creative activity of figuring out what should be true and why. This course is ideal for students who would like to learn about the reasoning underlying mathematical results, but at a pace and level of abstraction not as intense as Math 61CM/DM, as a consequence benefiting from additional opportunity to explore the reasoning. Familiarity with one-variable calculus is strongly recommended at least at the AB level of AP Calculus since a significant part of the course develops some of the main results in that material systematically from a small list of axioms. We also address linear algebra from the viewpoint of a mathematician, illuminating notions such as fields and abstract vector spaces. This course may be paired with Math 51; though that course is not a pre- or co-requisite.

MATH 61CM. Modern Mathematics: Continuous Methods. 5 Units.
This is the first part of a theoretical (i.e., proof-based) sequence in multivariable calculus and linear algebra, providing a unified treatment of these topics. Covers general vector spaces, linear maps and duality, eigenvalues, inner product spaces, spectral theorem, metric spaces, differentiation in Euclidean space, submanifolds of Euclidean space as local graphs, integration on Euclidean space, and many examples. The linear algebra content is covered jointly with Math 61DM. Students should know 1-variable calculus and have an interest in a theoretical approach to the subject. Prerequisite: score of 5 on the BC-level Advanced Placement calculus exam, or consent of the instructor.

MATH 61DM. Modern Mathematics: Discrete Methods. 5 Units.
This is the first part of a theoretical (i.e., proof-based) sequence in discrete mathematics and linear algebra. Covers general vector spaces, linear maps and duality, eigenvalues, inner product spaces, spectral theorem, counting techniques, and linear algebra methods in discrete mathematics including spectral graph theory and dimension arguments. The linear algebra content is covered jointly with Math 61CM. Students should have an interest in a theoretical approach to the subject. Prerequisite: score of 5 on the BC-level Advanced Placement calculus exam, or consent of the instructor.nnThis sequence is not appropriate for students planning to major in natural sciences, economics, or engineering, but is suitable for majors in any other field (such as MCS ("data science"), computer science, and mathematics).

MATH 62CM. Modern Mathematics: Continuous Methods. 5 Units.
A proof-based introduction to manifolds and the general Stokes' theorem. This includes a treatment of multilinear algebra, further study of submanifolds of Euclidean space (with many examples), differential forms and their geometric interpretations, integration of differential forms, Stokes' theorem, and some applications to topology. Prerequisites: Math 61CM.

MATH 62DM. Modern Mathematics: Discrete Methods. 5 Units.
This is the second part of a theoretical (proof-based) sequence with a focus on discrete mathematics. The central objects discussed in this course are finite fields. These are beautiful structures in themselves, and very useful in large areas of modern mathematics, and beyond. Our goal will be to construct these, understand their structure, and along the way discuss unexpected applications in combinatorics and number theory. Highlights of the course include a complete proof of a polynomial time algorithm for primality testing, Sidon sets and finite projective planes, and an understanding of a lovely magic trick due to Persi Diaconis. Prerequisite: Math 61DM or 61CM.

MATH 63CM. Modern Mathematics: Continuous Methods. 5 Units.
A proof-based course on ordinary differential equations. Topics include the inverse and implicit function theorems, implicitly-defined submanifolds of Euclidean space, linear systems of differential equations and necessary tools from linear algebra, stability and asymptotic properties of solutions to linear systems, existence and uniqueness theorems for nonlinear differential equations, behavior of solutions near an equilibrium point, and Sturm-Liouville theory. Prerequisite: Math 61CM or Math 61DM.

MATH 63DM. Modern Mathematics: Discrete Methods. 5 Units.
Third part of a proof-based sequence in discrete mathematics, though independent of the second part (62DM). The first half of the quarter gives a brisk-paced coverage of probability and random processes with an intensive use of generating functions and a rich variety of applications. The second half treats entropy, Bayesian inference, Markov chains, game theory, probabilistic methods in solving non-probabilistic problems. We use continuous calculus, e.g. in handling the Gaussian, but anything needed will be reviewed in a self-contained manner. Prerequisite: Math 61DM or 61CM.

MATH 70SI. The Game of Go: Strategy, Theory, and History. 1 Unit.
Strategy and mathematical theories of the game of Go, with guest appearance by a professional Go player.

MATH 80Q. Capillary Surfaces: Explored and Unexplored Territory. 3 Units.
Preference to sophomores. Capillary surfaces: the interfaces between fluids that are adjacent to each other and do not mix. Recently discovered phenomena, predicted mathematically and subsequently confirmed by experiments, some done in space shuttles. Interested students may participate in ongoing investigations with affinity between mathematics and physics.

MATH 87Q. Mathematics of Knots, Braids, Links, and Tangles. 3 Units.
Preference to sophomores. Types of knots and how knots can be distinguished from one another by means of numerical or polynomial invariants. The geometry and algebra of braids, including their relationships to knots. Topology of surfaces. Brief summary of applications to biology, chemistry, and physics.

MATH 101. Math Discovery Lab. 3 Units.
MDL is a discovery-based project course in mathematics. Students work independently in small groups to explore open-ended mathematical problems and discover original mathematics. Students formulate conjectures and hypotheses; test predictions by computation, simulation, or pure thought; and present their results to classmates. No lecture component; in-class meetings reserved for student presentations, attendance mandatory. Admission is by application: http://math101.stanford.edu. Motivated students with any level of mathematical background are encouraged to apply. WIM.

MATH 104. Applied Matrix Theory. 3 Units.
Linear algebra for applications in science and engineering: orthogonality, projections, spectral theory for symmetric matrices, the singular value decomposition, the QR decomposition, least-squares, the condition number of a matrix, algorithms for solving linear systems. MATH 113 offers a more theoretical treatment of linear algebra. MATH 104 and ENGR 108 cover complementary topics in applied linear algebra. The focus of MATH 104 is on algorithms and concepts; the focus of ENGR 108 is on a few linear algebra concepts, and many applications. Prerequisites: MATH 51 and programming experience on par with CS 106.

MATH 106. Functions of a Complex Variable. 3 Units.
Complex numbers, analytic functions, Cauchy-Riemann equations, complex integration, Cauchy integral formula, residues, elementary conformal mappings. (Math 116 offers a more theoretical treatment.) Prerequisite: 52.

MATH 107. Graph Theory. 3 Units.
An introductory course in graph theory establishing fundamental concepts and results in variety of topics. Topics include: basic notions, connectivity, cycles, matchings, planar graphs, graph coloring, matrix-tree theorem, conditions for hamiltonicity, Kuratowski's theorem, Ramsey and Turan-type theorem. Prerequisites: 51 or equivalent and some familiarity with proofs is required.

MATH 108. Introduction to Combinatorics and Its Applications. 3 Units.
Topics: graphs, trees (Cayley's Theorem, application to phylogony), eigenvalues, basic enumeration (permutations, Stirling and Bell numbers), recurrences, generating functions, basic asymptotics. Prerequisites: 51 or equivalent.

MATH 109. Applied Group Theory. 3 Units.
Applications of the theory of groups. Topics: elements of group theory, groups of symmetries, matrix groups, group actions, and applications to combinatorics and computing. Applications: rotational symmetry groups, the study of the Platonic solids, crystallographic groups and their applications in chemistry and physics. Honors math majors and students who intend to do graduate work in mathematics should take 120. WIM. Prerequisite: Math 51.

MATH 110. Applied Number Theory and Field Theory. 3 Units.
Number theory and its applications to modern cryptography. Topics: congruences, finite fields, primality testing and factorization, public key cryptography, error correcting codes, and elliptic curves, emphasizing algorithms. Includes an introduction to proof-writing. WIM. Prerequisite: Math 51.

MATH 113. Linear Algebra and Matrix Theory. 3 Units.
Algebraic properties of matrices and their interpretation in geometric terms. The relationship between the algebraic and geometric points of view and matters fundamental to the study and solution of linear equations. Topics: linear equations, vector spaces, linear dependence, bases and coordinate systems; linear transformations and matrices; similarity; eigenvectors and eigenvalues; diagonalization. Includes an introduction to proof-writing. (Math 104 offers a more application-oriented treatment.) Prerequisites: Math 51.

MATH 114. Introduction to Scientific Computing. 3 Units.
Introduction to Scientific Computing Numerical computation for mathematical, computational, physical sciences and engineering: error analysis, floating-point arithmetic, nonlinear equations, numerical solution of systems of algebraic equations, banded matrices, least squares, unconstrained optimization, polynomial interpolation, numerical differentiation and integration, numerical solution of ordinary differential equations, truncation error, numerical stability for time dependent problems and stiffness. Implementation of numerical methods in MATLAB programming assignments. Prerequisites: MATH 51, 52, 53; prior programming experience (MATLAB or other language at level of CS 106A or higher).
Same as: CME 108

MATH 115. Functions of a Real Variable. 3 Units.
The development of real analysis in Euclidean space: sequences and series, limits, continuous functions, derivatives, integrals. Basic point set topology. Includes introduction to proof-writing. Prerequisite: 21.

MATH 116. Complex Analysis. 3 Units.
Analytic functions, Cauchy integral formula, power series and Laurent series, calculus of residues and applications, conformal mapping, analytic continuation, introduction to Riemann surfaces, Fourier series and integrals. (Math 106 offers a less theoretical treatment.) Prerequisites: 52, and 115 or 171.

MATH 118. Mathematics of Computation. 3 Units.
Notions of analysis and algorithms central to modern scientific computing: continuous and discrete Fourier expansions, the fast Fourier transform, orthogonal polynomials, interpolation, quadrature, numerical differentiation, analysis and discretization of initial-value and boundary-value ODE, finite and spectral elements. Prerequisites: MATH 51 and 53.

MATH 120. Groups and Rings. 3 Units.
Recommended for Mathematics majors and required of honors Mathematics majors. Similar to 109 but altered content and more theoretical orientation. Groups acting on sets, examples of finite groups, Sylow theorems, solvable and simple groups. Fields, rings, and ideals; polynomial rings over a field; PID and non-PID. Unique factorization domains. WIM course. Prerequisite: Math 51 and some prior proof-writing experience.

MATH 121. Galois Theory. 3 Units.
Field of fractions, splitting fields, separability, finite fields. Galois groups, Galois correspondence, examples and applications. Prerequisite: Math 120 and (also recommended) 113.

MATH 122. Modules and Group Representations. 3 Units.
Modules over PID. Tensor products over fields. Group representations and group rings. Maschke's theorem and character theory. Character tables, construction of representations. Prerequisite: Math 120. Also recommended: 113.

MATH 131P. Partial Differential Equations. 3 Units.
An introduction to PDE; particularly suitable for non-Math majors. Topics include physical examples of PDE's, method of characteristics, D'Alembert's formula, maximum principles, heat kernel, Duhamel's principle, separation of variables, Fourier series, Harmonic functions, Bessel functions, spherical harmonics. Students who have taken MATH 171 should consider taking MATH 173 rather than 131P. Prerequisite: 53.

MATH 136. Stochastic Processes. 3 Units.
Introduction to measure theory, Lp spaces and Hilbert spaces. Random variables, expectation, conditional expectation, conditional distribution. Uniform integrability, almost sure and Lp convergence. Stochastic processes: definition, stationarity, sample path continuity. Examples: random walk, Markov chains, Gaussian processes, Poisson processes, Martingales. Construction and basic properties of Brownian motion. Prerequisite: STATS 116 or MATH 151 or equivalent. Recommended: MATH 115 or equivalent. http://statweb.stanford.edu/~adembo/math-136/.
Same as: STATS 219

MATH 137. Mathematical Methods of Classical Mechanics. 3 Units.
Newtonian mechanics. Lagrangian formalism. E. Noether's theorem. Oscillations. Rigid bodies. Introduction to symplectic geometry. Hamiltonian formalism. Legendre transform. Variational principles. Geometric optics. Introduction to the theory of integrable systems. Prerequisites: 51, 52, 53, or 61CM, 62CM, 63CM.

MATH 138. Celestial Mechanics. 3 Units.
Mathematically rigorous introduction to the classical N-body problem: the motion of N particles evolving according to Newton's law. Topics include: the Kepler problem and its symmetries; other central force problems; conservation theorems; variational methods; Hamilton-Jacobi theory; the role of equilibrium points and stability; and symplectic methods. Prerequisites: 53, and 115 or 171.

MATH 143. Differential Geometry. 3 Units.
Geometry of curves and surfaces in three-space and higher dimensional manifolds. Parallel transport, curvature, and geodesics. Surfaces with constant curvature. Minimal surfaces.

MATH 144. Introduction to Topology and Geometry. 3 Units.
Point set topology, including connectedness, compactness, countability and separation axioms. The inverse and implicit function theorems. Smooth manifolds, immersions and submersions, embedding theorems. Prerequisites: Math 61CM, or Math 51 and familiarity with linear algebra and analysis arguments at the level of 113 and 115 respectively.

MATH 145. Algebraic Geometry. 3 Units.
An introduction to the methods and concepts of algebraic geometry. The point of view and content will vary over time, but include: affine varieties, Hilbert basis theorem and Nullstellensatz, projective varieties, algebraic curves. Required: 120. Strongly recommended: additional mathematical maturity via further basic background with fields, point-set topology, or manifolds.

MATH 147. Differential Topology. 3 Units.
Introduction to smooth methods in topology including tranvsersality, intersection number, fixed point theorems, as well as differential forms and integration. Prerequisites: Math 62CM or Math 144.

MATH 148. Algebraic Topology. 3 Units.
Fundamental group, covering spaces, Euler characteristic, homology, classification of surfaces, knots. Prerequisite: 109 or 120.

MATH 151. Introduction to Probability Theory. 3 Units.
A proof-oriented development of basic probability theory. Counting; axioms of probability; conditioning and independence; expectation and variance; discrete and continuous random variables and distributions; joint distributions and dependence; Central Limit Theorem and laws of large numbers. nPrerequisite: Either Math 61CM or Math 52, and Math 115 or equivalent.

MATH 152. Elementary Theory of Numbers. 3 Units.
Euclid's algorithm, fundamental theorems on divisibility; prime numbers; congruence of numbers; theorems of Fermat, Euler, Wilson; congruences of first and higher degrees; quadratic residues; introduction to the theory of binary quadratic forms; quadratic reciprocity; partitions.

MATH 154. Algebraic Number Theory. 3 Units.
Properties of number fields and Dedekind domains, quadratic and cyclotomic fields, applications to some classical Diophantine equations. Prerequisites: 120 and 121, especially modules over principal ideal domains and Galois theory of finite fields.

MATH 155. Analytic Number Theory. 3 Units.
Introduction to Dirichlet series and Dirichlet characters, Poisson summation, Gauss sums, analytic continuation for Dirichlet L-functions, applications to prime numbers (e.g., prime number theorem, Dirichlet's theorem). Prerequisites: Complex analysis (Math 106 or 116), Math 152 (or comparable familiarity with the Euclidean algorithm, multiplicative group modulo n, and quadratic reciprocity), and experience with basic analysis arguments.

MATH 158. Basic Probability and Stochastic Processes with Engineering Applications. 3 Units.
Calculus of random variables and their distributions with applications. Review of limit theorems of probability and their application to statistical estimation and basic Monte Carlo methods. Introduction to Markov chains, random walks, Brownian motion and basic stochastic differential equations with emphasis on applications from economics, physics and engineering, such as filtering and control. Prerequisites: exposure to basic probability.
Same as: CME 298

MATH 159. Discrete Probabilistic Methods. 3 Units.
Modern discrete probabilistic methods suitable for analyzing discrete structures of the type arising in number theory, graph theory, combinatorics, computer science, information theory and molecular sequence analysis. Prerequisite: STATS 116/MATH 151 or equivalent. Typically in alternating years.

MATH 161. Set Theory. 3 Units.
Informal and axiomatic set theory: sets, relations, functions, and set-theoretical operations. The Zermelo-Fraenkel axiom system and the special role of the axiom of choice and its various equivalents. Well-orderings and ordinal numbers; transfinite induction and transfinite recursion. Equinumerosity and cardinal numbers; Cantor's Alephs and cardinal arithmetic. Open problems in set theory. Prerequisite: students should be comfortable doing proofs.

MATH 171. Fundamental Concepts of Analysis. 3 Units.
Recommended for Mathematics majors and required of honors Mathematics majors. Similar to 115 but altered content and more theoretical orientation. Properties of Riemann integrals, continuous functions and convergence in metric spaces; compact metric spaces, basic point set topology. Prerequisite: 61CM or 61DM or 115 or consent of the instructor. WIM.

MATH 172. Lebesgue Integration and Fourier Analysis. 3 Units.
Similar to 205A, but for undergraduate Math majors and graduate students in other disciplines. Topics include Lebesgue measure on Euclidean space, Lebesgue integration, L^p spaces, the Fourier transform, the Hardy-Littlewood maximal function and Lebesgue differentiation. Prerequisite: 171 or consent of instructor.

MATH 173. Theory of Partial Differential Equations. 3 Units.
A rigorous introduction to PDE accessible to advanced undergraduates. Elliptic, parabolic, and hyperbolic equations in many space dimensions including basic properties of solutions such as maximum principles, causality, and conservation laws. Methods include the Fourier transform as well as more classical methods. The Lebesgue integral will be used throughout, but a summary of its properties will be provided to make the course accessible to students who have not had 172 or 205A. In years when Math 173 is not offered, Math 220 is a recommended alternative (with similar content but a different emphasis). Prerequisite: 171 or equivalent.

MATH 175. Elementary Functional Analysis. 3 Units.
Linear operators on Hilbert space. Spectral theory of compact operators; applications to integral equations. Elements of Banach space theory. Prerequisite: 115 or 171.

MATH 177. Geometric Methods in the Theory of Ordinary Differential Equations. 3 Units.
Hamiltonian systems and their geometry. First order PDE and Hamilton-Jacobi equation. Structural stability and hyperbolic dynamical systems. Completely integrable systems. Perturbation theory.

MATH 193. Polya Problem Solving Seminar. 1 Unit.
Topics in mathematics and problem solving strategies with an eye towards the Putnam Competition. Topics may include parity, the pigeonhole principle, number theory, recurrence, generating functions, and probability. Students present solutions to the class. Open to anyone with an interest in mathematics.

MATH 197. Senior Honors Thesis. 1-6 Unit.
Honors math major working on senior honors thesis under an approved advisor carries out research and reading. Satisfactory written account of progress achieved during term must be submitted to advisor before term ends. May be repeated 3 times for a max of 9 units. Contact department student services specialist to enroll.

MATH 198. Practical Training. 1 Unit.
Only for undergraduate students majoring in mathematics. Students obtain employment in a relevant industrial or research activity to enhance their professional experience. Students submit a concise report detailing work activities, problems worked on, and key results. May be repeated for credit up to 3 units. Prerequisite: qualified offer of employment and consent of department. Prior approval by Math Department is required; you must contact the Math Department's Student Services staff for instructions before being granted permission to enroll.

MATH 199. Reading Topics. 1-3 Unit.
For Math majors only. Undergraduates pursue a reading program under the direction of a Math faculty member; topics limited to those not in regular department course offerings. Credit can fulfill the elective requirement for Math majors. Departmental approval required; please contact the Student Services Specialist for the enrollment proposal form at least 2 weeks before the final study list deadline. May be repeated for credit. Enrollment beyond a third section requires additional approval.

MATH 205A. Real Analysis. 3 Units.
Basic measure theory and the theory of Lebesgue integration. Prerequisite: 171 or equivalent.nnNOTE: Undergraduates require instructor permission to enroll. Undergraduates interested in taking the course should contact the instructor for permission, providing information about relevant background such as performance in prior coursework, reading, etc.

MATH 205B. Real Analysis. 3 Units.
Point set topology, basic functional analysis, Fourier series, and Fourier transform. Prerequisites: 171 and 205A or equivalent.nnNOTE: Undergraduates require instructor permission to enroll. Undergraduates interested in taking the course should contact the instructor for permission, providing information about relevant background such as performance in prior coursework, reading, etc.

MATH 205C. Real Analysis. 3 Units.
Continuation of 205B.nnNOTE: Undergraduates require instructor permission to enroll. Undergraduates interested in taking the course should contact the instructor for permission, providing information about relevant background such as performance in prior coursework, reading, etc.

MATH 210A. Modern Algebra I. 3 Units.
Basic commutative ring and module theory, tensor algebra, homological constructions, linear and multilinear algebra, canonical forms and Jordan decomposition. Prerequisite: 121 and 122 or equivalent.nnNOTE: Undergraduates require instructor permission to enroll. Undergraduates interested in taking the course should contact the instructor for permission, providing information about relevant background such as performance in prior coursework, reading, etc.

MATH 210B. Modern Algebra II. 3 Units.
Continuation of 210A. Topics in field theory, commutative algebra, algebraic geometry, and finite group representations. Prerequisites: 210A, and 121 or equivalent.nnNOTE: Undergraduates require instructor permission to enroll. Undergraduates interested in taking the course should contact the instructor for permission, providing information about relevant background such as performance in prior coursework, reading, etc.

MATH 210C. Lie Theory. 3 Units.
Topics in Lie groups, Lie algebras, and/or representation theory. Prerequisite: Math 210A and familiarity with the basics of finite group representations. When the course is on Lie groups, familiarity with tangent spaces and integration on manifolds is assumed. May be repeated for credit.nnNOTE: Undergraduates require instructor permission to enroll. Undergraduates interested in taking the course should contact the instructor for permission, providing information about relevant background such as performance in prior coursework, reading, etc.

MATH 215A. Algebraic Topology. 3 Units.
Topics: fundamental group and covering spaces, basics of homotopy theory, homology and cohomology (simplicial, singular, cellular), products, introduction to topological manifolds, orientations, Poincare duality. Prerequisites: 113, 120, and 171.nnNOTE: Undergraduates require instructor permission to enroll. Undergraduates interested in taking the course should contact the instructor for permission, providing information about relevant background such as performance in prior coursework, reading, etc.

MATH 215B. Differential Topology. 3 Units.
Topics: Basics of differentiable manifolds (tangent spaces, vector fields, tensor fields, differential forms), embeddings, tubular neighborhoods, integration and Stokes' Theorem, deRham cohomology, intersection theory via Poincare duality, Morse theory. Prerequisite: 215AnnNOTE: Undergraduates require instructor permission to enroll. Undergraduates interested in taking the course should contact the instructor for permission, providing information about relevant background such as performance in prior coursework, reading, etc.

MATH 215C. Differential Geometry. 3 Units.
This course will be an introduction to Riemannian Geometry. Topics will include the Levi-Civita connection, Riemann curvature tensor, Ricci and scalar curvature, geodesics, parallel transport, completeness, geodesics and Jacobi fields, and comparison techniques. Prerequisites 146 or 215BnnNOTE: Undergraduates require instructor permission to enroll. Undergraduates interested in taking the course should contact the instructor for permission, providing information about relevant background such as performance in prior coursework, reading, etc.

MATH 216A. Introduction to Algebraic Geometry. 3 Units.
Algebraic varieties, and introduction to schemes, morphisms, sheaves, and the functorial viewpoint. May be repeated for credit. Prerequisites: 210AB or equivalent.nnNOTE: Undergraduates require instructor permission to enroll. Undergraduates interested in taking the course should contact the instructor for permission, providing information about relevant background such as performance in prior coursework, reading, etc.

MATH 216B. Introduction to Algebraic Geometry. 3 Units.
Continuation of 216A. May be repeated for credit.nnNOTE: Undergraduates require instructor permission to enroll. Undergraduates interested in taking the course should contact the instructor for permission, providing information about relevant background such as performance in prior coursework, reading, etc.

MATH 216C. Introduction to Algebraic Geometry. 3 Units.
Continuation of 216B. May be repeated for credit.nnNOTE: Undergraduates require instructor permission to enroll. Undergraduates interested in taking the course should contact the instructor for permission, providing information about relevant background such as performance in prior coursework, reading, etc.

MATH 217C. Complex Differential Geometry. 3 Units.
Complex structures, almost complex manifolds and integrability, Hermitian and Kahler metrics, connections on complex vector bundles, Chern classes and Chern-Weil theory, Hodge and Dolbeault theory, vanishing theorems, Calabi-Yau manifolds, deformation theory.

MATH 220. Partial Differential Equations of Applied Mathematics. 3 Units.
First-order partial differential equations; method of characteristics; weak solutions; elliptic, parabolic, and hyperbolic equations; Fourier transform; Fourier series; and eigenvalue problems. Prerequisite: Basic coursework in multivariable calculus and ordinary differential equations, and some prior experience with a proof-based treatment of the material as in Math 171 or Math 61CM.nnNOTE: Undergraduates require instructor permission to enroll. Undergraduates interested in taking the course should contact the instructor for permission, providing information about relevant background such as performance in prior coursework, reading, etc.
Same as: CME 303

MATH 221A. Mathematical Methods of Imaging. 3 Units.
Image denoising and deblurring with optimization and partial differential equations methods. Imaging functionals based on total variation and l-1 minimization. Fast algorithms and their implementation.
Same as: CME 321A

MATH 221B. Mathematical Methods of Imaging. 3 Units.
Array imaging using Kirchhoff migration and beamforming, resolution theory for broad and narrow band array imaging in homogeneous media, topics in high-frequency, variable background imaging with velocity estimation, interferometric imaging methods, the role of noise and inhomogeneities, and variational problems that arise in optimizing the performance of array imaging algorithms.
Same as: CME 321B

MATH 226. Numerical Solution of Partial Differential Equations. 3 Units.
Hyperbolic partial differential equations: stability, convergence and qualitative properties; nonlinear hyperbolic equations and systems; combined solution methods from elliptic, parabolic, and hyperbolic problems. Examples include: Burger's equation, Euler equations for compressible flow, Navier-Stokes equations for incompressible flow. Prerequisites: MATH 220 or CME 302.nnNOTE: Undergraduates require instructor permission to enroll. Undergraduates interested in taking the course should contact the instructor for permission, providing information about relevant background such as performance in prior coursework, reading, etc.
Same as: CME 306

MATH 227. Partial Differential Equations and Diffusion Processes. 3 Units.
Parabolic and elliptic partial differential equations and their relation to diffusion processes. First order equations and optimal control. Emphasis is on applications to mathematical finance. Prerequisites: MATH 136/STATS 219 (or equivalents) and MATH 131P + MATH 115/171 or MATH 173 or MATH 220.

MATH 228. Stochastic Methods in Engineering. 3 Units.
The basic limit theorems of probability theory and their application to maximum likelihood estimation. Basic Monte Carlo methods and importance sampling. Markov chains and processes, random walks, basic ergodic theory and its application to parameter estimation. Discrete time stochastic control and Bayesian filtering. Diffusion approximations, Brownian motion and an introduction to stochastic differential equations. Examples and problems from various applied areas. Prerequisites: exposure to probability and background in analysis.
Same as: CME 308, MS&E 324

MATH 228A. Probability, Stochastic Analysis and Applications. 3 Units.
The basic limit theorems of probability theory and their application to maximum likelihood estimation. Basic Monte Carlo methods and importance sampling. Markov chains and processes, random walks, basic ergodic theory and its application to parameter estimation. Discrete time stochastic control and Bayesian filtering. Diffusion approximations, Brownian motion and basic stochastic differential equations. Examples and problems from various applied areas. Prerequisites: exposure to probability and background in analysis.

MATH 230A. Theory of Probability I. 3 Units.
Mathematical tools: sigma algebras, measure theory, connections between coin tossing and Lebesgue measure, basic convergence theorems. Probability: independence, Borel-Cantelli lemmas, almost sure and Lp convergence, weak and strong laws of large numbers. Large deviations. Weak convergence; central limit theorems; Poisson convergence; Stein's method. Prerequisites: STATS 116, MATH 171.
Same as: STATS 310A

MATH 230B. Theory of Probability II. 3 Units.
Conditional expectations, discrete time martingales, stopping times, uniform integrability, applications to 0-1 laws, Radon-Nikodym Theorem, ruin problems, etc. Other topics as time allows selected from (i) local limit theorems, (ii) renewal theory, (iii) discrete time Markov chains, (iv) random walk theory,n(v) ergodic theory. http://statweb.stanford.edu/~adembo/stat-310b. Prerequisite: 310A or MATH 230A.
Same as: STATS 310B

MATH 230C. Theory of Probability III. 3 Units.
Continuous time stochastic processes: martingales, Brownian motion, stationary independent increments, Markov jump processes and Gaussian processes. Invariance principle, random walks, LIL and functional CLT. Markov and strong Markov property. Infinitely divisible laws. Some ergodic theory. Prerequisite: 310B or MATH 230B. http://statweb.stanford.edu/~adembo/stat-310c/.
Same as: STATS 310C

MATH 231. Mathematics and Statistics of Gambling. 3 Units.
Probability and statistics are founded on the study of games of chance. Nowadays, gambling (in casinos, sports and the Internet) is a huge business. This course addresses practical and theoretical aspects. Topics covered: mathematics of basic random phenomena (physics of coin tossing and roulette, analysis of various methods of shuffling cards), odds in popular games, card counting, optimal tournament play, practical problems of random number generation. Prerequisites: Statistics 116 and 200.
Same as: STATS 334

MATH 232. Topics in Probability: Percolation Theory. 3 Units.
An introduction to first passage percolation and related general tools and models. Topics include early results on shape theorems and fluctuations, more modern development using hyper-contractivity, recent breakthrough regarding scaling exponents, and providing exposure to some fundamental long-standing open problems. Course prerequisite: graduate-level probability.

MATH 233A. Topics in Combinatorics. 3 Units.
A topics course in combinatorics and related areas. The topic will be announced by the instructor.nnNOTE: Undergraduates require instructor permission to enroll. Undergraduates interested in taking the course should contact the instructor for permission, providing information about relevant background such as performance in prior coursework, reading, etc.

MATH 233B. Topics in Combinatorics. 3 Units.
A topics course in combinatorics and related areas. The topic will be announced by the instructor.nnNOTE: Undergraduates require instructor permission to enroll. Undergraduates interested in taking the course should contact the instructor for permission, providing information about relevant background such as performance in prior coursework, reading, etc.

MATH 233C. Topics in Combinatorics. 3 Units.
A topics course in combinatorics and related areas. The topic will be announced by the instructor.

MATH 234. Large Deviations Theory. 3 Units.
Combinatorial estimates and the method of types. Large deviation probabilities for partial sums and for empirical distributions, Cramer's and Sanov's theorems and their Markov extensions. Applications in statistics, information theory, and statistical mechanics. Prerequisite: MATH 230A or STATS 310. Offered every 2-3 years. http://statweb.stanford.edu/~adembo/large-deviations/.
Same as: STATS 374

MATH 235A. Topics in combinatorics. 3 Units.
This advanced course in extremal combinatorics covers several major themes in the area. These include extremal combinatorics and Ramsey theory, the graph regularity method, and algebraic methods.

MATH 235B. Modern Markov Chain Theory. 3 Units.
This is a graduate-level course on the use and analysis of Markov chains. Emphasis is placed on explicit rates of convergence for chains used in applications to physics, biology, and statistics. Topics covered: basic constructions (metropolis, Gibbs sampler, data augmentation, hybrid Monte Carlo); spectral techniques (explicit diagonalization, Poincaré, and Cheeger bounds); functional inequalities (Nash, Sobolev, Log Sobolev); probabilistic techniques (coupling, stationary times, Harris recurrence). A variety of card shuffling processes will be studies. Central Limit and concentration.nnNOTE: Undergraduates require instructor permission to enroll. Undergraduates interested in taking the course should contact the instructor for permission, providing information about relevant background such as performance in prior coursework, reading, etc.

MATH 235C. Topics in Markov Chains. 3 Units.
Classical functional inequalities (Nash, Faber-Krahn, log-Sobolev inequalities), comparison of Dirichlet forms. Random walks and isoperimetry of amenable groups (with a focus on solvable groups). Entropy, harmonic functions, and Poisson boundary (following Kaimanovich-Vershik theory).

MATH 236. Introduction to Stochastic Differential Equations. 3 Units.
Brownian motion, stochastic integrals, and diffusions as solutions of stochastic differential equations. Functionals of diffusions and their connection with partial differential equations. Random walk approximation of diffusions. Prerequisite: 136 or equivalent and differential equations.nnNOTE: Undergraduates require instructor permission to enroll. Undergraduates interested in taking the course should contact the instructor for permission, providing information about relevant background such as performance in prior coursework, reading, etc.

MATH 237. Default and Systemic Risk. 3 Units.
Introduction to mathematical models of complex static and dynamic stochastic systems that undergo sudden regime change in response to small changes in parameters. Examples from materials science (phase transitions), power grid models, financial and banking systems. Special emphasis on mean field models and their large deviations, including computational issues. Dynamic network models of financial systems and their stability.

MATH 237A. Topics in Financial Math: Market microstructure and trading algorithms. 3 Units.
Introduction to market microstructure theory, including optimal limit order and market trading models. Random matrix theory covariance models and their application to portfolio theory. Statistical arbitrage algorithms.

MATH 238. Mathematical Finance. 3 Units.
Stochastic models of financial markets. Forward and futures contracts. European options and equivalent martingale measures. Hedging strategies and management of risk. Term structure models and interest rate derivatives. Optimal stopping and American options. Corequisites: MATH 236 and 227 or equivalent.nnNOTE: Undergraduates require instructor permission to enroll. Undergraduates interested in taking the course should contact the instructor for permission, providing information about relevant background such as performance in prior coursework, reading, etc.
Same as: STATS 250

MATH 239. Computation and Simulation in Finance. 3 Units.
Monte Carlo, finite difference, tree, and transform methods for the numerical solution of partial differential equations in finance. Emphasis is on derivative security pricing. Prerequisite: 238 or equivalent.

MATH 243. Functions of Several Complex Variables. 3 Units.
Holomorphic functions in several variables, Hartogs phenomenon, d-bar complex, Cousin problem. Domains of holomorphy. Plurisubharmonic functions and pseudo-convexity. Stein manifolds. Coherent sheaves, Cartan Theorems A&B. Levi problem and its solution. Grauert's Oka principle. Prerequisites: MATH 215A and experience with manifolds. NOTE: Undergraduates require instructor permission to enroll. Undergraduates interested in taking the course should contact the instructor for permission, providing information about relevant background such as performance in prior coursework, reading, etc.

MATH 244. Riemann Surfaces. 3 Units.
Riemann surfaces and holomorphic maps, algebraic curves, maps to projective spaces. Calculus on Riemann surfaces. Elliptic functions and integrals. Riemann-Hurwitz formula. Riemann-Roch theorem, Abel-Jacobi map. Uniformization theorem. Hyperbolic surfaces. (Suitable for advanced undergraduates.) Prerequisites: MATH 106 or MATH 116, and familiarity with surfaces equivalent to MATH 143, MATH 146, or MATH 147.

MATH 245A. Topics in Algebraic Geometry. 3 Units.
Topics of contemporary interest in algebraic geometry. May be repeated for credit.nnNOTE: Undergraduates require instructor permission to enroll. Undergraduates interested in taking the course should contact the instructor for permission, providing information about relevant background such as performance in prior coursework, reading, etc.

MATH 245B. Topics in Algebraic Geometry. 3 Units.
May be repeated for credit.nnNOTE: Undergraduates require instructor permission to enroll. Undergraduates interested in taking the course should contact the instructor for permission, providing information about relevant background such as performance in prior coursework, reading, etc.

MATH 245C. Topics in Algebraic Geometry. 3 Units.
May be repeated for credit.

MATH 246. Topics in number theory: L-functions. 3 Units.
The Riemann Zeta function and Dirichlet L-functions, zero-free regions and vertical distribution of the zeros, primes in arithmetic progressions, the class number problem, Hecke L-functions and Tate's thesis, Artin L-functions and the Chebotarev density theorem, Modular forms and Maass forms.nnPrerequisites: Algebraic Number Theory.

MATH 248. Introduction to Ergodic Theory. 3 Units.
Topics may include 1) subadditive and multiplicative ergodic theorems, 2) notions of mixing, weak mixing, spectral theory, 3) metric and topological entropy of dynamical systems, 4) measures of maximal entropy. Prerequisites: Solid background in "Measure and Integration" (Math 205A) and some functional analysis, including Riesz representation theorem and Hahn-Banach theorem (Math 205B).

MATH 249A. Topics in number theory. 3 Units.
Topics of contemporary interest in number theory. May be repeated for credit.nnNOTE: Undergraduates require instructor permission to enroll. Undergraduates interested in taking the course should contact the instructor for permission, providing information about relevant background such as performance in prior coursework, reading, etc.

MATH 249B. Topics in Number Theory. 3 Units.
NOTE: Undergraduates require instructor permission to enroll. Undergraduates interested in taking the course should contact the instructor for permission, providing information about relevant background such as performance in prior coursework, reading, etc.

MATH 249C. Topics in Number Theory. 3 Units.
NOTE: Undergraduates require instructor permission to enroll. Undergraduates interested in taking the course should contact the instructor for permission, providing information about relevant background such as performance in prior coursework, reading, etc.

MATH 256A. Partial Differential Equations. 3 Units.
The theory of linear and nonlinear partial differential equations, beginning with linear theory involving use of Fourier transform and Sobolev spaces. Topics: Schauder and L2 estimates for elliptic and parabolic equations; De Giorgi-Nash-Moser theory for elliptic equations; nonlinear equations such as the minimal surface equation, geometric flow problems, and nonlinear hyperbolic equations.nnNOTE: Undergraduates require instructor permission to enroll. Undergraduates interested in taking the course should contact the instructor for permission, providing information about relevant background such as performance in prior coursework, reading, etc.

MATH 256B. Partial Differential Equations. 3 Units.
Continuation of 256A.

MATH 257A. Symplectic Geometry and Topology. 3 Units.
Linear symplectic geometry and linear Hamiltonian systems. Symplectic manifolds and their Lagrangian submanifolds, local properties. Symplectic geometry and mechanics. Contact geometry and contact manifolds. Relations between symplectic and contact manifolds. Hamiltonian systems with symmetries. Momentum map and its properties. May be repeated for credit.nnNOTE: Undergraduates require instructor permission to enroll. Undergraduates interested in taking the course should contact the instructor for permission, providing information about relevant background such as performance in prior coursework, reading, etc.

MATH 257B. Symplectic Geometry and Topology. 3 Units.
Continuation of 257A. May be repeated for credit.nnNOTE: Undergraduates require instructor permission to enroll. Undergraduates interested in taking the course should contact the instructor for permission, providing information about relevant background such as performance in prior coursework, reading, etc.

MATH 257C. Symplectic Geometry and Topology. 3 Units.
Continuation of 257B. May be repeated for credit.

MATH 258. Topics in Geometric Analysis. 3 Units.
May be repeated for credit.nnNOTE: Undergraduates require instructor permission to enroll. Undergraduates interested in taking the course should contact the instructor for permission, providing information about relevant background such as performance in prior coursework, reading, etc.

MATH 262. Applied Fourier Analysis and Elements of Modern Signal Processing. 3 Units.
Introduction to the mathematics of the Fourier transform and how it arises in a number of imaging problems. Mathematical topics include the Fourier transform, the Plancherel theorem, Fourier series, the Shannon sampling theorem, the discrete Fourier transform, and the spectral representation of stationary stochastic processes. Computational topics include fast Fourier transforms (FFT) and nonuniform FFTs. Applications include Fourier imaging (the theory of diffraction, computed tomography, and magnetic resonance imaging) and the theory of compressive sensing. NOTE: Undergraduates require instructor permission to enroll. Undergraduates interested in taking the course should contact the instructor for permission, providing information about relevant background such as performance in prior coursework, reading, etc.
Same as: CME 372

MATH 263A. Topics in Representation Theory: Affine Lie Algebras and Modular Forms. 3 Units.
Kac-Moody Lie algebras are infinite-dimensional Lie algebras whose theory is remarkably similar to finite-dimensional semisimple Lie algebras. Affine Lie algebras are the most important special case.We will develop some of the Kac-Moody theory, such as the Kac-Weyl character formula, before specializing to affine Lie algebras. Ideas from physics give a multiplication called fusion on the irreducible integrable representations of fixed level. Kac and Peterson showed that the characters and related "string functions" of these representations are modular forms, and the transformation properties of these theta functions of fixed level encode important information about the fusion ring. NOTE: Undergraduates require instructor permission to enroll. Undergraduates interested in taking the course should contact the instructor for permission, providing information about relevant background such as performance in prior coursework, reading, etc. May be repeated for credit.

MATH 263B. Crystal Bases: Representations and Combinatorics. 3 Units.
Crystal Bases are combinatorial analogs of representation theorynof Lie groups. We will explore different aspects of thesenanalogies and develop rigorous purely combinatorial foundations.

MATH 263C. Topics in Representation Theory. 3 Units.
Conformal Field Theory is a branch of physics with origins in solvable lattice models and string theory. But the mathematics that it has inspired has many applications in pure mathematics.nWe will give an introduction to this theory with related representation theories of the Virasoro and affine Lie algebras, and vertex operators.nnPrerequisites: we will not assume any particular knowledge from physics, but some knowledge of Lie algebras will be helpful.nnNOTE: Undergraduates require instructor permission to enroll. Undergraduates interested in taking the course should contact the instructor for permission, providing information about relevant background such as performance in prior coursework, reading, etc.nnnMay be repeated for credit.

MATH 269. Topics in symplectic geometry. 3 Units.
May be repeated for credit.

MATH 270. Geometry and Topology of Complex Manifolds. 3 Units.
Complex manifolds, Kahler manifolds, curvature, Hodge theory, Lefschetz theorem, Kahler-Einstein equation, Hermitian-Einstein equations, deformation of complex structures. May be repeated for credit.

MATH 271. The H-Principle. 3 Units.
The language of jets. Thom transversality theorem. Holonomic approximation theorem. Applications: immersion theory and its generaliazations. Differential relations and Gromov's h-principle for open manifolds. Applications to symplectic geometry. Microflexibility. Mappings with simple singularities and their applications. Method of convex integration. Nash-Kuiper C^1-isometric embedding theorem.

MATH 272. Topics in Partial Differential Equations. 3 Units.
NOTE: Undergraduates require instructor permission to enroll. Undergraduates interested in taking the course should contact the instructor for permission, providing information about relevant background such as performance in prior coursework, reading, etc.

MATH 273. Topics in Mathematical Physics. 3 Units.
Covers a list of topics in mathematical physics. The specific topics may vary from year to year, depending on the instructor's discretion. Background in graduate level probability theory and analysis is desirable.
Same as: STATS 359

MATH 275. Topics in Applied Mathematics: A World of Flows II. 3 Units.
The purpose of this course is to show beautiful surprises and instructive paradoxes in a maximal diversity of fluid phenomena, and to understand them with minimal models. The prerequisites are fluency in the so-called "mathematical methods", plus ability to think physics at the advanced undergraduate level. The content will be the same as that of winter 2019 (but different from that of winter 2020). nnNOTE: Undergraduates must obtain instructor permission and pass a test to enroll. Undergraduates interested in taking the course should contact the instructor no later than the first week of class, providing information about performance in prior coursework.

MATH 280. Evolution Equations in Differential Geometry. 3 Units.
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MATH 282A. Low Dimensional Topology. 3 Units.
The theory of surfaces and 3-manifolds. Curves on surfaces, the classification of diffeomorphisms of surfaces, and Teichmuller space. The mapping class group and the braid group. Knot theory, including knot invariants. Decomposition of 3-manifolds: triangulations, Heegaard splittings, Dehn surgery. Loop theorem, sphere theorem, incompressible surfaces. Geometric structures, particularly hyperbolic structures on surfaces and 3-manifolds. May be repeated for credit up to 6 total units.

MATH 282B. Homotopy Theory. 3 Units.
Homotopy groups, fibrations, spectral sequences, simplicial methods, Dold-Thom theorem, models for loop spaces, homotopy limits and colimits, stable homotopy theory. May be repeated for credit up to 6 total units.nnNOTE: Undergraduates require instructor permission to enroll. Undergraduates interested in taking the course should contact the instructor for permission, providing information about relevant background such as performance in prior coursework, reading, etc.

MATH 282C. Fiber Bundles and Cobordism. 3 Units.
Possible topics: principal bundles, vector bundles, classifying spaces. Connections on bundles, curvature. Topology of gauge groups and gauge equivalence classes of connections. Characteristic classes and K-theory, including Bott periodicity, algebraic K-theory, and indices of elliptic operators. Spectral sequences of Atiyah-Hirzebruch, Serre, and Adams. Cobordism theory, Pontryagin-Thom theorem, calculation of unoriented and complex cobordism. May be repeated for credit up to 6 total units.

MATH 283A. Topics in Topology. 3 Units.
Topics of contemporary interest in topology. NOTE: Undergraduates require instructor permission to enroll. Undergraduates interested in taking the course should contact the instructor for permission, providing information about relevant background such as performance in prior coursework, reading, etc.

MATH 284. Topics in Geometric Topology. 3 Units.
Incompressible surfaces, irreducible manifolds, prime decomposition, Morse theory, Heegaard diagrams, Heegaard splittings, the Thurston norm, sutured manifold theory, Heegaard Floer homology, sutured Floer homology.

MATH 286. Topics in Differential Geometry. 3 Units.
Topics of contemporary interest in differential geometry. May be repeated for credit.nnNOTE: Undergraduates require instructor permission to enroll. Undergraduates interested in taking the course should contact the instructor for permission, providing information about relevant background such as performance in prior coursework, reading, etc.

MATH 298. Graduate Practical Training. 1 Unit.
Only for mathematics graduate students. Students obtain employment in a relevant industrial or research activity to enhance their professional experience. Students submit a concise report detailing work activities, problems worked on, and key results. May be repeated for credit up to 3 units. Prerequisite: qualified offer of employment and consent of department. Prior approval by Math Department is required; you must contact the Math Department's Student Services staff for instructions before being granted permission to enroll.

MATH 301. Advanced Topics in Convex Optimization. 3 Units.
Modern developments in convex optimization: semidefinite programming; novel and efficient first-order algorithms for smooth and nonsmooth convex optimization. Emphasis on numerical methods suitable for large scale problems arising in science and engineering. Prerequisites: convex optimization (EE 364), linear algebra (Math 104), numerical linear algebra (CME 302); background in probability, statistics, real analysis and numerical optimization.
Same as: CME 375

MATH 305. Applied mathematics through toys and magic. 3 Units.
This course is a series of case-studies in doing applied mathematics on surprising phenomena we notice in daily life. Almost every class will show demos of these phenomena (toys and magic) and suggest open projects. The topics range over a great variety and cut across areas traditionally pigeonholed as physics, biology, engineering, computer science, mathematics ¿ but, instead of developing sophisticated mathematics on simple material, our aim is to extract simple mathematical understanding from sophisticated material which, at first, we may not yet know how to pigeonhole. In each class I will try to make the discussion self-contained and to give everybody something to take home, regardless of the background.

MATH 355. Graduate Teaching Seminar. 1 Unit.
Required of and limited to first-year Mathematics graduate students.

MATH 360. Advanced Reading and Research. 1-10 Unit.
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MATH 382. Qualifying Examination Seminar. 1-3 Unit.
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MATH 391. Seminar on Logic & Formal Philosophy. 2-4 Units.
Research seminar for graduate students working in logic and formal philosophy. Presentations on contemporary topics by seminar participants and outside visitors. Maybe be repeated for credit.
Same as: PHIL 391

MATH 802. TGR Dissertation. 0 Units.
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