Mathematics

Degrees Offered

- Master of Science
- Doctor of Philosophy

Programs

The Department of Mathematics offers graduate programs leading to the Master of Science (M.S.) and Doctor of Philosophy (Ph.D.) degrees. The master's degree program offers specializations in pure mathematics, applied mathematics, industrial/applied/interdisciplinary mathematics, and mathematics for secondary educators. The Ph.D. program provides for a common core of fundamental mathematics followed by specialized studies culminating in an original research dissertation directed by a faculty advisor. Depending on the student's program and interests, there are diverse career opportunities available in education, government, and industry.

Financial Support

Many graduate students receive financial support in the form of a graduate teaching assistantship, which provides a stipend and a full waiver of university tuition. These are awarded taking into account primarily the student's academic record along with the letters of recommendation and any supplementary information reflecting on the student's potential for success in the program. In some cases, teaching experience and/or the potential for outstanding teaching can be a consideration. Teaching assistants have the opportunity to work with the mathematics education faculty of the Department's Institute for Mathematics Learning (IML). A small number of research assistantships are also available. Applications from students requesting financial aid should be received no later than February 15 to ensure full consideration for the subsequent fall semester. Late applications are accepted, but students are advised to check with the graduate director as to the availability of assistantships. Applications for admission (alone) can also be considered at other times, but for best consideration, particularly for the Ph.D. program, students should adhere to the February 15 deadline. Other financial aid includes partial university tuition waivers and part-time positions assisting in the instructional computer labs. TOEFL scores are required for international students whose native language is not English, with a university requirement of a 550 minimum score for admission.

Doctor of Philosophy

The doctor of philosophy is a research program in which the final product is an original, publishable research thesis. For students entering with regular admission status, the program requires a minimum of twenty-four hours of approved coursework along with research and graduate seminar requirements. As reflected in the interests and expertise of the faculty, students may specialize in a variety of areas of pure, applied, and discrete mathematics as well as research in undergraduate mathematics education.

EXAMINATIONS AND DISSERTATION

The student must pass the Department's Ph.D. Entrance Examination within two years: a student enrolling in a given calendar year must pass by the end of the spring semester two years after. The examination is over two subjects selected from the four areas of algebra, real analysis, differential equations, and topology.

Within three years of enrolling, the student is expected to pass a qualifying oral and written examination on the major and minor areas of study and present an approved dissertation prospectus. A minor examination is waived if the student has obtained at least a 3.5 GPA in the corresponding courses. If the qualifying examination results are unsatisfactory (U), the dissertation committee may reexamine the student once.

A Ph.D. candidate must complete a dissertation, representing at least twenty-four hours of 700-level research credit, under the supervision of a dissertation advisor. The research upon which the dissertation is based must conform to scholastic standards and constitute an original and publishable contribution to mathematics.

COMBINATORIAL COMPUTING AND DISCRETE MATHEMATICS (C.C.D.M.)

This is an option within the mathematics Ph.D. program, emphasizing interdisciplinary research at the intersection of computer science, statistics, and discrete mathematics. A minimum of thirty-three credit hours of coursework is required and includes designated core courses in discrete mathematics, statistics, and computer science. Students may undertake mathematics research of an interdisciplinary nature among these three areas.

LANGUAGE REQUIREMENT

Each Ph.D. student must demonstrate a reading knowledge of French, German, or Russian. The Graduate Programs Committee may approve the substitution of a different foreign language or a computer language for fulfillment of this requirement.

Further information may be obtained from the department's website at http://www.math.wvu.edu or by contacting the graduate director at gradprog@math.wvu.edu. Details on program requirements can be found in the Department's Graduate Handbook, available at http://www.math.wvu.edu/graduate_handbook.
FACULTY

CHAIR
• Edgar Fuller - Ph.D. (University of Georgia)

PROFESSORS
• Ian Christie - Ph.D. (University of Dundee)
  Emeritus, Numerical Partial Differential Equations
• Krzysztof Ciesielski
  Analysis, Topology, Set Theory
• Harvey Diamond - Ph.D. (MIT)
  Approximation Theory, Applied Mathematics
• Edgar Fuller - Ph.D. (University of Georgia)
  Geometric Knot Theory, Mathematics Education
• Harry Gingold - D.Sc. (Israel Institute of Technology)
  Differential Equations, Asymptotic Methods
• John Goldwasser
  Combinatorics, Graph Theory
• Henry W. Gould - M.A. (University of Virginia)
  Emeritus, Combinatorics, Number Theory, Special Functions
• Harumi Hattori - Ph.D. (Rensselaer Polytechnic Institute)
  Differential Equations, Continuum Mechanics
• Hong-Jian Lai
  Associate Chair, Graph Theory, Matroid Theory
• Dening Li
  Partial Differential Equations
• Rong Luo - Ph.D. (West Virginia University)
  Discrete Mathematics
• Laura Pyzdzowski - Ed.D. (West Virginia University)
  Mathematics Education, Instructional Technology
• Michael E. Mays - Ph.D. (Penn. State University)
  Director of the Institute for Mathematics Learning, Number Theory
• Sherman D. Riemenschneider - Ph.D. (Syracuse University)
  Emeritus, Approximation Theory, Wavelet Theory
• Jerzy Wojciechowski - Ph.D. (University of Cambridge)
  Combinatorics, Graph Theory
• Cun-Quan Zhang
  Graph Theory, Combinatorics

ASSOCIATE PROFESSOR
• Marjorie Darrah - Ph.D. (WVU)
  Educational Technology, Algorithm Development, K-12 Outreach
• Jessica Deshler - Ph.D. (University of New Mexico)
  Undergraduate Mathematics Education
• Gary H. Ganser
  Applied Mathematics, Fluid Mechanics, Numerical Analysis
• Adam Halasz - Ph.D. (State University of New York at Stony Brook)
  Mathematical Biology, Swarm Robotics
• David Miller - Ph.D. (Oklahoma State University)
  Undergraduate Mathematics Education, Cognitive Science
• James E. Moseley
  Partial Differential Equations, Modeling
• Vicki Sealey - Ph.D. (Arizona State University)
  Mathematics Education
• Adrian Tudorascu - Ph.D. (Carnegie Mellon University)
  Partial Differential Equations
ASSISTANT PROFESSOR

- Nicole Engelke-Infante
  Undergraduate Mathematics Education
- Kevin Milans - Ph.D. (University of Illinois at Urbana Champaign)
  Combinatorics, Graph Theory
- Charis Tsikkou
  Nonlinear PDE

Master’s Admission Information

Admission to the M.S. program requires a WVU admission application and submission of applicable transcripts. International students must supply a passing TOEFL score or other acceptable evidence of English proficiency. Students seeking financial aid should also supply an assistantship application and three letters of recommendation. GRE scores are not required.

Programs are available for students to study applied mathematics, pure mathematics, industrial/applied/interdisciplinary mathematics, or mathematics for secondary educators. For regular admission to the M.S. program, students should have the equivalent of an undergraduate major in mathematics, including at least one semester of advanced calculus (Math 451 or equivalent) and courses in linear algebra and modern algebra. Students with deficiencies may be admitted provisionally; deficiencies are expected to be made up in the first year of study. A minimum of three semesters of calculus is normally required for such admission, but students can often complete their remaining calculus courses during the summer prior to full-time enrollment. To be in good standing, a student is expected to maintain at least a 3.0 average (B) in mathematics courses and to present at least a 3.0 average in all work offered in fulfillment of the degree program.

ADVISORY COMMITTEE

Each student will be assigned an advisory committee consisting of at least three members of the graduate faculty. This committee will assist the student in designing a written plan of study that takes into account the student’s interests and needs as well as the aims of the department’s graduate programs. Later changes in the plan are possible only through mutual agreement of the student and the committee.

PROGRAMS

The student’s plan of study is developed in one of these programs: applied mathematics, pure mathematics, industrial/applied/interdisciplinary mathematics, or mathematics for secondary educators. The programs are designed either for students who intend to pursue a doctor of philosophy in mathematics or the mathematical sciences or for those planning to seek employment in education, government, or industry. Depending upon the program selected, thirty to thirty-three semester hours of approved coursework are required.

Note: MATH 590/690/696/697/790/797 may not be counted for credit to satisfy graduate course requirements.

EXAMINATIONS/THESSES/PROJECTS

Upon beginning graduate study, all M.S. students are given a basic exam in advanced calculus and linear algebra for purposes of course placement. Depending on the program chosen, students must complete examinations, a thesis, or a project as a graduation requirement.

Ph.D. Admission Requirements

For regular admission, applicants for the Ph.D. program must have completed a graduate degree similar to the M.S. in mathematics. Students with an exceptionally strong undergraduate background may sometimes be admitted provisionally, with twelve–eighteen credit hours of additional coursework required.

The following materials should be submitted:

- A WVU admission application
- An application for financial support (optional)
- Official undergraduate and graduate transcripts
- Three letters of recommendation from individuals having experience with the applicant’s mathematical ability
- TOEFL or IELTS scores for students whose native language is not English

All doctoral students must demonstrate that they are prepared to undertake doctoral work and research by passing an entrance examination, given each year in April and August, within two years after enrolling. Specifically, students entering the program in a given calendar year must pass the entrance examination by the end of the spring semester in the calendar year two years after. Students must pass examinations in two areas from among the four areas of algebra, real analysis, topology, and differential equations. For students in the CCDM option (see below), one of these area exams is replaced by an examination over the CCDM core curriculum.

Beyond any coursework taken to remove deficiencies while a provisional student, a minimum of twenty-four hours of approved coursework is required of all doctoral students, which must include a major area of four courses and two minor areas of two courses each. Certain level and distribution
Requirements apply to a student’s program. In addition, doctoral students must enroll for one credit hour of graduate seminar each semester they are in residence.

Ph.D. students may choose the CCDM option, which requires a minimum of 33 credit hours of coursework and includes designated core courses in discrete mathematics, statistics, and computer science. Students may undertake mathematics research of an interdisciplinary nature among these three areas.

Dissertation Committee
After the above requirements are satisfied, a student must request that the Director of Graduate Studies select a dissertation committee of at least five members (with a dissertation advisor as chairperson and one member from outside the department) for them.

Master of Science
MAJOR REQUIREMENTS
A minimum GPA of 3.0 is required in all courses applied toward the degree.
A minimum grade of B or higher is required for Mathematics courses included in the program of study.

<table>
<thead>
<tr>
<th>Select an Area of Emphasis *</th>
<th>28-34</th>
</tr>
</thead>
<tbody>
<tr>
<td>MATH 543   Linear Algebra</td>
<td>3</td>
</tr>
</tbody>
</table>

Real Analysis Requirement

<table>
<thead>
<tr>
<th>MATH 451 &amp; MATH 452 or MATH 551</th>
<th>Introduction to Real Analysis 1 and Introduction to Real Analysis 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>MATH 694 Professional Tools</td>
<td>Real Variables 1</td>
</tr>
</tbody>
</table>

Total Hours 34-43

* At most four courses in the plan of study may be from outside mathematics.

Other Curriculum Requirements:
Students must also meet these option prerequisites:

- Partial differential equations (MATH 261 or MATH 465) (may be satisfied by taking MATH 522)
- Probability Theory (STAT 215 or STAT 461) (may be satisfied by taking STAT 561)

Students must complete at least two courses from Math 452, Math 541, Math 543, Math 551, Math 555, and Math 581 with a grade of at least B in each. Including required courses above, at least one course from 4 different groups below must be included. Within two different groups there must be a sequence of two suitably linked courses. Overall, at most 4 courses may be taken from outside the Mathematics Department, subject to approval by the Graduate Director.

I. Computation/optimization: MATH 521, MATH 522
II. Probability theory/mathematical statistics: STAT 561-562 (other approved STAT courses provided STAT 562 is taken)
III. Algebra/Discrete Math: MATH 541, MATH 543, MATH 571, MATH 573, MATH 545, MATH 645. CS courses as approved by the advisor and the Graduate Director
IV. Modeling: MATH 563, an approved course involving modeling, possibly outside Mathematics.
V. Mathematical Analysis: MATH 452, MATH 551, MATH 651, MATH 555
VI. Graduate courses (one 400-level possible with permission) from outside MATH/STAT/CS. These are to be approved by the Graduate Director.

Doctor of Philosophy
MAJOR REQUIREMENTS
Minimum GPA of 3.0 is required.
MATH 694 Seminar 2
or MATH 696 Graduate Seminar

Foreign Language Requirement

Complete the following coursework or select an area of emphasis:

<table>
<thead>
<tr>
<th>Area</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major Area</td>
<td>12</td>
</tr>
<tr>
<td>Minor Area 1</td>
<td>6</td>
</tr>
<tr>
<td>Minor Area 2</td>
<td>6</td>
</tr>
</tbody>
</table>

**Group A (Algebra/Number Theory/Discrete Mathematics/Set Theory) Courses and possible minor sequences:**

<table>
<thead>
<tr>
<th>Course Sequence</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>MATH 641 &amp; MATH 747 Modern Algebra 2 and Advanced Topics in Modern Algebra</td>
<td>12</td>
</tr>
<tr>
<td>MATH 745 &amp; MATH 746 Analytic Number Theory 1 and Analytic Number Theory 2</td>
<td>12</td>
</tr>
<tr>
<td>MATH 573 &amp; MATH 773 Graph Theory and Advanced Topics in Graph Theory</td>
<td>12</td>
</tr>
<tr>
<td>MATH 683 &amp; MATH 783 Set Theory and Applications and Set Theory and Applications</td>
<td>12</td>
</tr>
<tr>
<td>MATH 771 &amp; MATH 772 Matroid Theory 1 and Matroid Theory 2</td>
<td>12</td>
</tr>
</tbody>
</table>

Other electives in Group A as offered


<table>
<thead>
<tr>
<th>Course Sequence</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>MATH 751 &amp; MATH 752 Functional Analysis 1 and Functional Analysis 2</td>
<td>12</td>
</tr>
<tr>
<td>MATH 757 &amp; MATH 758 Theory of Partial Differential Equations 1 and Theory of Partial Differential Equations 2</td>
<td>12</td>
</tr>
</tbody>
</table>

Other electives in Group B as offered

One minor sequence may be chosen outside Groups A and B with permission of the Graduate Director, including:

<table>
<thead>
<tr>
<th>Course</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>MATH 791 ADTP: Rsrch- Undrgrd Math Ed 4</td>
<td>24</td>
</tr>
</tbody>
</table>

Research

Entrance Examination

Qualifying Examination

Dissertation Proposal

Dissertation

Dissertation Defense

Total Hours 50

**LANGUAGES REQUIREMENT**

Each Ph.D. student must demonstrate a reading knowledge of French, German, or Russian. The Graduate Programs Committee may approve the substitution of a different foreign language or a computer language for fulfillment of this requirement.

Further information may be obtained from the department's website at http://www.math.wvu.edu or by contacting the graduate director at gradprog@math.wvu.edu. Details on program requirements can be found in the Department's Graduate Handbook, available at http://www.math.wvu.edu/graduate_handbook.

**Applied Mathematics Area of Emphasis**

Students in this option must complete the four course RUME sequence. Students must also complete six additional mathematics courses, chosen from the areas in Groups A and B above in include at least four courses at the 700-level. At least two courses should be chosen from each group A and B so as to fulfill the requirements of a minor area. The remaining two courses can be used, for instance, to acquire additional breadth in mathematics or to achieve research level depth in an area. Course options are listed above. In cases where RUME 1-2 have been taken in the M.S program, only RUME 3-4 are required.

<table>
<thead>
<tr>
<th>Course Sequence</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>MATH 791 RUME 1-4</td>
<td>6-12</td>
</tr>
<tr>
<td>Minor Area 1</td>
<td>6</td>
</tr>
<tr>
<td>Minor Area 2</td>
<td>6</td>
</tr>
<tr>
<td>Electives</td>
<td>6</td>
</tr>
</tbody>
</table>
Discrete Mathematics Area of Emphasis

This option is provided for students who wish to work in the intersection of computing, discrete mathematics, and data analysis.

<table>
<thead>
<tr>
<th>Course</th>
<th>Title</th>
<th>Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS 520</td>
<td>Advanced Analysis of Algorithms</td>
<td>3</td>
</tr>
<tr>
<td>MATH 571</td>
<td>Combinatorial Analysis 1</td>
<td>3</td>
</tr>
<tr>
<td>MATH 573</td>
<td>Graph Theory</td>
<td>3</td>
</tr>
<tr>
<td>STAT 561</td>
<td>Theory of Statistics 1</td>
<td>3</td>
</tr>
</tbody>
</table>

A major area and minor areas, representing at least 24 hours at the doctoral level must be chosen from at least three of the groups listed below. For CCDM students with mathematics chairs, the major area and one of the minor areas must be taken within the Department of Mathematics. For CCDM students with mathematics and computer science/statistics co-chairs, either the major area or both of the minor areas must be taken within the Department of Mathematics.

Group A: Algebra/Number Theory/Discrete Mathematics/Set Theory

Group B: Analysis/Differential Equations/Numerical Analysis and Computational Mathematics/Topology

Group C: (CS courses) Algorithms, Automata Theory, Formal Languaged, Advanced graphics and image processing, Data Mining, Pattern Recognition, Artificial Intelligence

Group D: (STAT courses) Data Mining, Advanced Statistical Theory, Stochastic Processes, Bioinformatics

Total Hours: 48-54

Major Learning Outcomes

MATHEMATICS

The Department of Mathematics offers the M.S. and Ph.D. degrees and has programs emphasizing pure and applied mathematics (M.S., Ph.D.), mathematics for secondary educators (M.S.) and research in undergraduate mathematics education (Ph.D). Major goals include the following:

Students in the M.S. program receive broad, rigorous training in areas fundamental to mathematics, with options depending on their post-graduation goals:

- Master’s level students planning to continue graduate study will have a solid grounding in mathematics basic to their intended graduate programs.
- Students preparing for industry jobs will possess the breadth of applicable mathematical knowledge and experience needed for the challenges of mathematics in industry.
- Students preparing for secondary education will have a broad based deep appreciation of the core of mathematics and effective pedagogy.

Ph.D. students continue advanced training with the following goals:

- Obtain specialized, advanced training in a major field giving them a research-level background and the ability to contribute in their field.
- Under the mentorship of their thesis supervisor, conduct independent, original research in mathematics leading to a significant contribution in their field of study.
• Become acquainted with mathematical research in a variety of fields through course work, seminars, colloquia, and conference presentations.
• Gain significant experience in teaching at the university level and in communicating mathematics.

M.S. Examinations

Students in the Applied Mathematics area of emphasis must pass the M.S Advanced Exam by passing two subject area exams at the M.S level, taken from among Real Analysis, Algebra, Topology, and Differential Equations. No more than three attempts at any one subject area exam are permitted.

Students in the Pure Mathematics area of emphasis must pass the M.S. Advanced Exam by passing two subject area exams at the MS level, taken from among Real Analysis, Algebra, Topology, and Differential Equations. No more than three attempts at any one subject area exam are permitted.

Students in the Mathematics for Secondary Education area of emphasis must pass a final written examination based on their course work, consisting of four sections: algebra, geometry, applied/discrete mathematics, and probability/statistics. With the approval of the Advisory Committee, the exam may be taken after completion of the required 18 hours of graduate mathematics courses and the core curriculum.

Ph.D. Examinations

1) Students must pass the Ph.D. Entrance Examination by the end of their second year in the program. This entails passing two subject area exams at the Ph.D. level, from among Algebra, Real Analysis, Topology, and Differential equations. Any exam may be taken up to three times.

2) Students must pass the Qualifying Examination by the end of their third year. Students whose dissertation area is Research in Undergraduate Mathematics Education will be provided by their committee with a research assignment, based on content areas and research techniques in the field, to be completed over a four-week period. The results will be presented in written form and orally examined by the student's committee. Second, the student must present a thesis prospectus. The student's committee must approve the outcome of both the exam and the prospectus.

3) For each minor area in which the GPA is not 3.5 or above, as part of the Qualifying Exam, the student must take an exam over the minor area to assess competency.

COURSES

MATH 520. Solution of Nonlinear Systems. 3 Hours.

MATH 521. Numerical Analysis. 3 Hours.
PR: MATH 261 and computer language. Number systems and errors, interpolation by polynomials, linear systems, scalar algebraic equations and systems, optimization, approximation theory, integration initial, and boundary value problems.

MATH 522. Numerical Solution of PDE. 3 Hours.
PR: MATH 261 and computer language. Finite difference and finite element methods for elliptic, parabolic, and hyperbolic problems. Study of properties such as consistency, convergence, stability, conservation, and discrete maximum principles.

MATH 524. Middle School Number and Algebra 1. 2 Hours.
PR or CONC: C&I 524. Designed only for in service middle school and elementary mathematics teachers. Sets of numbers as examples of algebraic systems, properties of groups, rings, and fields.

MATH 525. Middle School Number and Algebra 2. 2 Hours.
PR or CONC: C&I 525. Continuation of MATH 524. Designed only for in service middle school and elementary mathematics teachers. Properties of polynomials and polynomial rings. Mathematics modeling with finite differences and least squares.

MATH 528. Middle School Functions and Change 1. 2 Hours.
PR or CONC: C&I 528. Designed only for in service middle school and elementary mathematics teachers. Function concept, operations on functions, limits, continuity, Intermediate Value Theorem, families of curves, optimization area. Classroom applications current research in learning. Applications in model curricula.

MATH 529. Middle School Functions and Change 2. 2 Hours.
PR or CONC: C&I 529. Continuation of MATH 528. Designed only for in service middle school and elementary mathematics teachers. Function concept, operations on functions, limits, continuity, Intermediate Value Theorem, families of curves, optimization area. Classroom applications current research in learning. Applications in model curricula.

MATH 530. Introduction to Applied Mathematics. 1-6 Hours.
PR: MATH 251. (Designed especially for secondary-school mathematics teachers; others admitted with departmental approval obtained before registration.) Problem solving and construction of mathematical models in the social, life, and physical sciences. Examples illustrating the origins and use of secondary school mathematics in solving real world problems.

MATH 533. Modern Algebra for Teachers 1. 3 Hours.
PR: MATH 251. (Designed especially for secondary-school mathematics teachers. Others admitted with departmental approval obtained prior to registration.) Introduction to algebraic structures; groups, rings, integral domains, and fields. Development and properties of the rational and real number systems.
MATH 534. Modern Algebra For Teachers 2. 3 Hours.
PR: MATH 341 or MATH 533. Further investigation of algebraic structures begun in MATH 533. (Emphasis on topics helpful to secondary-school mathematics teachers.) Topics include Sylow theory, Jordan-Holder Theorem, rings and quotients, field extensions, Galois theory and solution by radicals.

MATH 535. Foundations of Geometry. 3 Hours.
PR: MATH 251 (Designed especially for secondary mathematics teachers; others admitted with departmental approval obtained before registration.) Incidence geometrics with models; order for lines and planes; separation by angles and by triangles; congruence; introduction to Euclidean geometry; geometry.

MATH 536. Transformation Geometry. 3 Hours.
PR: MATH 341 or MATH 533. (Designed especially for secondary-school mathematics teachers; others admitted with departmental approval obtained before registration.) A modern approach to geometry based on transformations in a vector space setting. The course unifies the development of geometry with the methods of modern algebra.

MATH 541. Modern Algebra. 3 Hours.
PR: MATH 341 Concepts from set theory and the equivalence of the Axiom of Choice. Zorn’s Lemma and the Well-Ordering Theorem; a study of the structure of groups, rings, fields, and vector spaces; elementary factorization theory; extensions of ring and fields; modules and ideals; and lattices.

MATH 543. Linear Algebra. 3 Hours.
PR: MATH 441. Review of theory of groups and fields; linear vector spaces including the theory of duality; full linear group; bilinear and quadratic forms; and theory of isotropic and totally isotropic spaces.

MATH 545. Number Theory 1. 3 Hours.
PR: MATH 155 or MATH 156. Introduction to classical number theory covering such topics as divisibility, the Euclidean algorithm, Diophantine equations, congruencies, primitive roots, quadratic residues, number-theoretic functions, distribution of primes, irrationals, and combinatorial methods. Special numbers such as those of Bernoulli, Euler, and Stirling.

MATH 551. Real Variables 1. 3 Hours.

MATH 555. Complex Variables 1. 3 Hours.
PR: MATH 451. Number systems, the complex plane and its geometry. Holomorphic functions, power series, elementary functions, complex integration, representation theorems, the calculus of residues, analytic continuation and analytic function, elliptic functions, Holomorphic functions of several complex variables.

MATH 557. Calculus of Variations. 3 Hours.
PR: (MATH 261 and MATH 452) or MATH 568. Necessary conditions and sufficient conditions for weak and strong relative minimums of an integral, Euler-Lagrange equation. Legendre condition, field construction, Weierstrass excess function, and the Jacobi equation.

MATH 560. Introduction to Dynamical Systems and Applications. 3 Hours.
This course is an introduction to the theory of dynamical systems, whose goal is to study the behavior of systems with known laws of evolution. We cover basic topics including fixed points, periodic orbits, linearization, local and global behavior of solutions, bifurcations, and chaos. The theory will be accompanied by applications from biology, chemistry, and physics.

MATH 561. Geometric Modeling-Curves/Surf. 3 Hours.
PR: MATH 261 and linear algebra. Mathematical techniques used in CAD/CAM environments, including conics, cubic splines, Bezier splines, B-splines rational Bezier and B-splines, interpolation, geometric continuity, and data exchange.

MATH 563. Mathematics Modeling. 3 Hours.
PR: MATH 261 and MATH 465. This course is concerned with construction, analysis, and interpretation of mathematical models that shed light on important problems in the sciences. Emphasis is on the simplification, dimensional analysis, and scaling of mathematical models.

MATH 564. Intermediate Differential Equations. 3 Hours.

MATH 565. Wave Propagation. 3 Hours.
PR: MATH 465 or MATH 567 or Consent. Study of waves in applied mathematics. The wave equation and geometrical optics, water waves, exact solutions, and interacting solitary waves. Basic concepts of hyperbolic and dispersive waves, conservation laws and scalar PDE’s shock waves, Bateman Burgers equation, and hyperbolic systems.

MATH 567. Advanced Calculus. 3 Hours.
per semester. PR: MATH 261. Primarily for engineers and scientists. Functions of several variables, partial differentiation, implicit functions, transformations; line surface and volume integrals; point set theory, continuity, integration, infinite series and convergence, power series, and improper integrals.
MATH 568. Advanced Calculus. 3 Hours.
per semester. PR: MATH 567. Primarily for engineers and scientists. Functions of several variables, partial differentiation, implicit functions, transformations; line surface and volume integrals; point set theory, continuity, integration, infinite series and convergence, power series, and improper integrals.

MATH 569. Seminar in Applied Mathematics. 1-12 Hours.
PR: Consent. Selected topics in applied mathematics. Topics previously offered include applied linear algebra, computational fluid dynamics, numerical partial differential equations, ordinary differential equations, perturbation methods, and stochastic processes.

MATH 571. Combinatorial Analysis 1. 3 Hours.
PR: One year of calculus. Permutations, combinations, generating functions, principle of inclusion and exclusion, distributions, partitions, compositions, trees and networks.

MATH 573. Graph Theory. 3 Hours.
PR: MATH 343 and MATH 283. Basic concepts of graphs and digraphs, trees, cycles and circuits, connectivity, traversibility, planarity, colorability, and chromatic polynomials. Further topics from among factorization, line graph, covering and independence, graph matrices and groups, Ramsey theory, and packing theory.

MATH 578. Applied Discrete Mathematics. 3 Hours.
PR: MATH 375 or MATH 378 or MATH 341 or MATH 343 or MATH 283. Topics may include combinatorial optimization, applied coding theory, integer programming, linear programming, matching, and network flows.

MATH 581. Topology 1. 3 Hours.
PR: MATH 452. A detailed treatment of topological spaces covering the topics of continuity, convergence, compactness, and connectivity; product and identification space, function spaces, and the topology in Euclidean spaces.

MATH 590. Teaching Practicum. 1-3 Hours.
PR: Consent. Supervised practice in college teaching of mathematics. Note: This course is intended to insure that graduate assistants are adequately prepared and supervised when they are given college teaching responsibility. It will also present a mechanism for students not on assistantships to gain teaching experience. Grading will be P/F.

MATH 591. Advanced Topics. 1-6 Hours.
PR: Consent. Investigation of advanced topics not covered in regularly scheduled courses.

MATH 592. Directed Study. 1-6 Hours.
Directed study, reading, and/or research.

MATH 593. Special Topics. 1-6 Hours.
A study of contemporary topics selected from recent developments in the field.

MATH 595. Independent Study. 1-6 Hours.
Faculty supervised study of topics not available through regular course offerings.

MATH 621. Computational Matrix Theory. 3 Hours.
Matrix norms singular value decomposition, QR factorization, least-square problems, conditioning and stability, eigenvalue problems, and iterative methods for solving large systems.

MATH 631. RUME 1: Introduction to Undergraduate Mathematics Education Research. 3 Hours.
PR: (MATH 451 and MATH 452) or MATH 551 or MATH 567. Research literature will provide background for investigating issues in knowing and learning undergraduate mathematics. Students will be introduced to research design, data collection, and qualitative analysis related to investigating aspects of learning undergraduate mathematics.

MATH 641. Modern Algebra 2. 3 Hours.
PR: MATH 545. Concepts from set theory and the equivalence of the axiom of choice. Zorn’s Lemma and the Well-Ordering Theorem; a study of the structure of groups, rings, fields, and vector spaces; elementary factorization theory; extensions of ring and fields; modules and ideals; and lattices.

MATH 645. Number Theory 2. 3 Hours.
PR: MATH 305. Introduction to classical number theory covering such topics as divisibility, the Euclidean algorithm, Diophantine equations, congruencies, primitive roots, quadratic residues, number-theoretic functions distribution of primes, irrationals, and combinatorial methods. Special numbers such as those of Bernoulli, Euler, and Stirling.

MATH 651. Real Variables 2. 3 Hours.
PR: MATH 551. A development of the Lebesgue integral, function spaces and differentiation, complex measures, the Lebesgue-Radon- Nikodym theorem.

MATH 655. Complex Variables 2. 3 Hours.
PR: MATH 555. Number systems, the complex plane and its geometry. Holomorphic functions, power series, elementary functions, complex integration, representation theorems, the calculus of residues, analytic continuation and analytic function, elliptic functions, Holomorphic functions of several complex variables.
MATH 661. Geometric Modeling-Solids. 3 Hours.
PR: MATH 561. Mathematical techniques used in CAD/CAM environments, including basic primitives, manifold and non-manifold solids, Euler characteristic, half-space models, constructive solid geometry (CSG), boundary representation (B-rep), Euler operators, Boolean operations, and data exchange.

MATH 671. Combinatorial Analysis 2. 3 Hours.
PR: MATH 571. Permutations, combinations, generating functions, principle of inclusion and exclusion, distributions, partitions, compositions, trees, and networks.

MATH 677A. Topics in Discrete Mathematics. 3 Hours.
PR: MATH 571 or MATH 543 or MATH 573. Topics include algorithmic graph theory, combinatorial designs, matroid theory, (0,1)-matrices, and permanents.

MATH 677B. Topics in Discrete Mathematics. 3 Hours.
PR: MATH 571 or MATH 543 or MATH 573. Topics may include algorithmic graph theory, combinatorial designs, matroid theory, (0,1)-matrices, and permanents.

MATH 677C. Topics in Discrete Mathematics. 3 Hours.
PR: MATH 571 or MATH 543 or MATH 573. Topics may include algorithmic graph theory, combinatorial designs, matroid theory, (0,1)-matrices, and permanents.

MATH 677D. Topics in Discrete Mathematics. 3 Hours.
PR: MATH 571 or MATH 543 or MATH 573. Topics may include algorithmic graph theory, combinatorial designs, matroid theory, (0,1)-matrices, and permanents.

MATH 677E. Topics in Discrete Mathematics. 3 Hours.
PR: MATH 571 or MATH 543 or MATH 573. Topics may include algorithmic graph theory, combinatorial designs, matroid theory, (0,1)-matrices, and permanents.

MATH 677F. Topics in Discrete Mathematics. 3 Hours.
PR: MATH 571 or MATH 543 or MATH 573. Topics may include algorithmic graph theory, combinatorial designs, matroid theory, (0,1)-matrices, and permanents.

MATH 677G. Topics in Discrete Mathematics. 3 Hours.
PR: MATH 571 or MATH 543 or MATH 573. Topics may include algorithmic graph theory, combinatorial designs, matroid theory, (0,1)-matrices, and permanents.

MATH 677H. Topics in Discrete Mathematics. 3 Hours.
PR: MATH 571 or MATH 543 or MATH 573. Topics may include algorithmic graph theory, combinatorial designs, matroid theory, (0,1)-matrices, and permanents.

MATH 677I. Topics in Discrete Mathematics. 3 Hours.
PR: MATH 571 or MATH 543 or MATH 573. Topics may include algorithmic graph theory, combinatorial designs, matroid theory, (0,1)-matrices, and permanents.

MATH 677J. Topics in Discrete Mathematics. 3 Hours.
PR: MATH 571 or MATH 543 or MATH 573. Topics may include algorithmic graph theory, combinatorial designs, matroid theory, (0,1)-matrices, and permanents.

MATH 677K. Topics in Discrete Mathematics. 3 Hours.
PR: MATH 571 or MATH 543 or MATH 573. Topics may include algorithmic graph theory, combinatorial designs, matroid theory, (0,1)-matrices, and permanents.

MATH 677L. Topics in Discrete Mathematics. 3 Hours.
PR: MATH 571 or MATH 543 or MATH 573. Topics may include algorithmic graph theory, combinatorial designs, matroid theory, (0,1)-matrices, and permanents.

MATH 677M. Topics in Discrete Mathematics. 3 Hours.
PR: MATH 571 or MATH 543 or MATH 573. Topics may include algorithmic graph theory, combinatorial designs, matroid theory, (0,1)-matrices, and permanents.

MATH 677N. Topics in Discrete Mathematics. 3 Hours.
PR: MATH 571 or MATH 543 or MATH 573. Topics may include algorithmic graph theory, combinatorial designs, matroid theory, (0,1)-matrices, and permanents.

MATH 677O. Topics in Discrete Mathematics. 3 Hours.
PR: MATH 571 or MATH 543 or MATH 573. Topics may include algorithmic graph theory, combinatorial designs, matroid theory, (0,1)-matrices, and permanents.
MATH 677Q. Topics in Discrete Mathematics. 3 Hours.
PR: MATH 571 or MATH 543 or MATH 573. Topics may include algorithmic graph theory, combinatorial designs, matroid theory, \((0,1)\)-matrices, and permanents.

MATH 677R. Topics in Discrete Mathematics. 3 Hours.
PR: MATH 571 or MATH 543 or MATH 573. Topics may include algorithmic graph theory, combinatorial designs, matroid theory, \((0,1)\)-matrices, and permanents.

MATH 677S. Topics in Discrete Mathematics. 3 Hours.
PR: MATH 571 or MATH 543 or MATH 573. Topics may include algorithmic graph theory, combinatorial designs, matroid theory, \((0,1)\)-matrices, and permanents.

MATH 677T. Topics in Discrete Mathematics. 3 Hours.
PR: MATH 571 or MATH 543 or MATH 573. Topics may include algorithmic graph theory, combinatorial designs, matroid theory, \((0,1)\)-matrices, and permanents.

MATH 677U. Topics in Discrete Mathematics. 3 Hours.
PR: MATH 571 or MATH 543 or MATH 573. Topics may include algorithmic graph theory, combinatorial designs, matroid theory, \((0,1)\)-matrices, and permanents.

MATH 677V. Topics in Discrete Mathematics. 3 Hours.
PR: MATH 571 or MATH 543 or MATH 573. Topics may include algorithmic graph theory, combinatorial designs, matroid theory, \((0,1)\)-matrices, and permanents.

MATH 677W. Topics in Discrete Mathematics. 3 Hours.
PR: MATH 571 or MATH 543 or MATH 573. Topics may include algorithmic graph theory, combinatorial designs, matroid theory, \((0,1)\)-matrices, and permanents.

MATH 677X. Topics in Discrete Mathematics. 3 Hours.
PR: MATH 571 or MATH 543 or MATH 573. Topics may include algorithmic graph theory, combinatorial designs, matroid theory, \((0,1)\)-matrices, and permanents.

MATH 681. Topology 2. 3 Hours.
PR: MATH 581. A detailed treatment of topological spaces covering the topics of continuity, convergence, compactness, and connectivity; product and identification space, function spaces, and the topology in Euclidean spaces.

MATH 683. Set Theory and Applications. 3 Hours.
PR: MATH 541 or MATH 551 or MATH 581. The course concentrates on the typical methods of set theory, transfinite induction, and Zorn's Lemma with emphasis on their applications outside set theory. The fundamentals of logic and basic set theory are included.

MATH 690. Teaching Practicum. 1-3 Hours.
PR: Consent. Supervised practice in college teaching of mathematics. Note: This course is intended to insure that graduate assistants are adequately prepared and supervised when they are given college teaching responsibility. It also provides a mechanism for students not on assistantships to gain teaching experience. (Grading will be S/U.).

MATH 691. Advanced Topics. 1-6 Hours.
PR: Consent. Investigation of advanced topics not covered in regularly scheduled courses.

MATH 692. Directed Study. 1-6 Hours.
Directed study, reading, and/or research.

MATH 693. Special Topics. 1-6 Hours.
A study of contemporary topics selected from recent developments in the field.

MATH 694. Seminar. 1-6 Hours.
Special seminars arranged for advanced graduate students.

MATH 695. Independent Study. 1-6 Hours.
Faculty supervised study of topics not available through regular course offerings.

MATH 696. Graduate Seminar. 1 Hour.
PR: Consent. Each graduate student will present at least one seminar to the assembled faculty and graduate student body of his or her program.
MATH 697. Research. 1-15 Hours.
PR: Consent. Research activities leading to thesis, problem report, research paper or equivalent scholarly project or a dissertation. (Grading may be S/ U.).

MATH 698. Thesis or Dissertation. 1-6 Hours.
PR: Consent. This is an optional course for programs that wish to provide formal supervision during the writing of student reports (698), or dissertations (798). Grading is normal.

MATH 699. Graduate Colloquium. 1-6 Hours.
PR: Consent. For graduate students not seeking coursework credit but who wish to meet residency requirements, use of the University's facilities, and participate in it academic and cultural programs. Note: Graduate students who are not actively involved in coursework or research are entitled, through enrollment in their department's 699/799 Graduate Colloquium to consult with graduate faculty, participate in both formal and informal academic activities sponsored by their program, and retain all of the rights and privileges of duly enrolled students. Grading is P/F; colloquium credit may not be counted against credit requirements for masters programs. Registration for one credit of 699/799 graduate colloquium satisfies the University requirement of registration in the semester in which graduation occurs.

MATH 732. RUME 2: Learning Theories. 3 Hours.
PR: MATH 631. Students will investigate learning theories related to undergraduate mathematics education research and use these learning theories to formulate research questions and to collect and analyze data.

MATH 733. RUME 3: Advanced Learning Theories. 3 Hours.
PR: MATH 732. Students will expand their understanding of learning theories related to undergraduate mathematics education research and their ability to use these learning theories to formulate research questions and to collect and analyze data.

MATH 741. Group Theory 1. 3 Hours.
PR: MATH 741.

MATH 742. Group Theory 2. 3 Hours.
PR: MATH 741.

MATH 745. Analytic Number Theory 1. 3 Hours.
PR: MATH 555 and MATH 645. Selected topics in analytic number theory such as the prime number theorem, primes in an arithmetical progression, the Zeta function, the Goldbach conjecture.

MATH 746. Analytic Number Theory 2. 3 Hours.
PR: MATH 745. Selected topics in analytic number theory such as the prime number theorem, primes in an arithmetical progression, the Zeta function, the Goldbach conjecture.

MATH 747. Advanced Topics in Modern Algebra. 1-6 Hours.
This course will cover selected topics of modern algebra as an extension of the basic material covered in the 541-641 sequence. The topic will be selected from algebraic number theory, noncommutative rings and modules, representation theory, algebraic model theory, homological algebra. (May be repeated for credit with consent.)

MATH 750. Seminar in Analysis. 1-12 Hours.

MATH 751. Functional Analysis 1. 3 Hours.
PR: MATH 551. A study of Banach and Hilbert spaces; the Hahn-Banach theorem, uniform boundedness principle, and the open mapping theorem; dual spaces and the Riesz representation theorem; Banach algebras; and spectral theory.

MATH 752. Functional Analysis 2. 3 Hours.
PR: MATH 751. A study of Banach and Hilbert spaces; the Hahn-Banach theorem, uniform boundedness principle, and the open mapping theorem; dual spaces and the Riesz representation theorem; Banach algebras; C* algebras; spectral theory.

MATH 753. Special Functions. 3 Hours.
PR: MATH 261 and MATH 452. Operational techniques, generalized hypergeometric functions, classical polynomials of Bell, Hermite, Legendre, Noerlund, etc. Introduction to recent polynomial systems. Current research topics.

MATH 757. Theory of Partial Differential Equations 1. 3 Hours.

MATH 758. Theory of Partial Differential Equations 2. 3 Hours.

MATH 764. Asymptotic Methods. 3 Hours.
MATH 764. Asymptotic Methods. 3 hr. PR: MATH 564. Study of asymptotic methods for differential equations. Basic concepts - asymptotic expansions, asymptotic approximation; asymptotic evaluations of integrals - Laplace's methods, Kelvin's methods, the steepest descent; asymptotic solutions of equations; perturbation of eigenvectors; the difference between singular and regular perturbations; multiple scale analysis; the method of matched asymptotic expansions; perturbations of periodic systems.
MATH 771. Matroid Theory 1. 3 Hours.
PR: (MATH 541 or MATH 543) and (MATH 571 or MATH 573). Independent sets, circuits, bases, rank functions, closure operators and close sets, other axiom systems, geometric representations, duality and minors, linear and algebraic representability, connectivity, basics of partial ordered sets, flats and lattices, relationship between lattices and matroids.

MATH 772. Matroid Theory 2. 3 Hours.
PR: MATH 771. Matroid representability, representability over finite fields, algebraic matroids, matroid constructions, higher connectivity of matroids, binary and ternary matroids, the splitter theorem and its applications, submodular functions, matroid intersection theorem, matroids in combinatorial optimizations.

MATH 773. Advanced Topics in Graph Theory. 3 Hours.
PR: MATH 573. (May be repeated for credit toward graduation.) Topics may include: Algebraic graph theory, random graph theory, extremal graph theory, topological graph theory, and structural graph theory.

MATH 777. Advanced Topics in Combinatorics. 3 Hours.
PR: MATH 571 or MATH 677. Topics may include: Combinatorics on finite sets, probabilistic methods in combinatorics, enumerations, Polya Theory, combinatorial matroid theory, coding theory, combinatorial identities, infinite combinatorics, transversal theory, and matroid theory. (May be repeated for credit with consent.).

MATH 780. Seminar in Topology. 1-12 Hours.

MATH 781. Continuum Theory 1. 3 Hours.
PR: MATH 581. The fundamental properties of continua (compact, connected, metric spaces), including boundary bumping, space filling curves, structure of special continua, and inverse limits.

MATH 782. Continuum Theory 2. 3 Hours.
PR: MATH 781. The fundamental properties of continua (compact, connected, metric spaces), including boundary bumping, space filling curves, structure of special continua, and inverse limits.

MATH 783. Set Theory and Applications. 3 Hours.
PR: MATH 683. The course elaborates on the applications of the transfinite induction, and combines recursion methods with other elements of modern set theory, including the use of additional axioms of set theory, introduction to the forcing method.

MATH 790. Teaching Practicum. 1-3 Hours.
PR: Consent. Supervised practice in college teaching of mathematics. Note: This course is intended to insure that graduate assistants are adequately prepared and supervised when they are given college teaching responsibility. It will also present a mechanism for students not on assistantships to gain teaching experience. (Grading will be S/U.).

MATH 791. Advanced Topics. 1-6 Hours.
PR: Consent. Investigation of advanced topics not covered in regularly scheduled courses.

MATH 792. Directed Study. 1-6 Hours.
Directed study, reading, and/or research.

MATH 793. Special Topics. 1-6 Hours.
A study of contemporary topics selected from recent developments in the field.

MATH 794. Seminar. 1-6 Hours.
Special seminars arranged for advanced graduate students.

MATH 795. Independent Study. 1-9 Hours.
Faculty supervised study of topics not available through regular course offerings.

MATH 796. Graduate Seminar. 1 Hour.
PR: Consent. Each graduate student will present at least on seminar to the assembled faculty and graduate student body of his or her program.

MATH 797. Research. 1-15 Hours.
PR: Consent. Research activities leading to thesis, problem report, research paper or equivalent scholarly project, or dissertation. (Grading may be S/U.).

MATH 798. Thesis or Dissertation. 1-6 Hours.
PR: Consent. This is an optional course for programs that wish to provide formal supervision during the writing of student reports (698), or dissertations (798). Grading is normal.

MATH 799. Graduate Colloquium. 1-6 Hours.
PR: Consent. For graduate students not seeking coursework credit but who wish to meet residency requirements, use of the University's facilities, and participate in its academic and cultural programs. Note: Graduate students who are not actively involved in coursework or research are entitled, through enrollment in their department's 699/799 Graduate Colloquium to consult with graduate faculty, participate in both formal and informal academic activities sponsored by their program, and retain all of the rights and privileges of duly enrolled students. Grading is P/F; colloquium credit may not be counted against credit requirements for masters programs. Registration for one credit of 699/799 graduate colloquium satisfies the University requirement of registration in the semester in which graduation occurs.
MATH 930. Professional Development. 1-6 Hours.
Professional development courses provide skill renewal or enhancement in a professional field or content area (e.g., education, community health, geology). These tuition-waived continuing education courses are graded on a pass/fail grading scale and do not apply as graduate credit toward a degree program.