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departmental offices, and study space can also be reserved in the university library. Students may access the departments Unix and NT machines and the university's three mainframes from terminals in the department.

The Department of Mathematics is also home to the Japan-U.S. Mathematics Institute (JAMI), which each year invites six or more outstanding mathematicians from Japan. These visitors organize weekly seminars attended by graduate students and faculty.

Undergraduate Programs

Course Scheduling

Students usually begin by taking Calculus I-II, which is offered in three versions to meet the needs of students with different goals and interests. Students in mathematics, the physical sciences, and engineering are encouraged to begin with the 110.108-109 sequence or honors 110.113; students majoring in other subjects may wish to take the 110.106-107 sequence which relates the methods of calculus to the biological and social sciences. A one-term pre-calculus course 110.105 is offered for students who could benefit from additional preparation in the basic tools (algebra and trigonometry) used in calculus.

Entering students may receive course credit for Calculus I or Calculus I-II on the basis of the College Board AP exams. Students without AP credit should take a departmental placement exam to determine which course would be appropriate for them. For more information regarding placement, please visit: www.math.jhu.edu.

Linear Algebra (110.201), Calculus III (110.202), and Differential Equations (110.302) may be taken in any order after completing Calculus II (110.107 or 110.109). These courses are especially designed to acquaint students with mathematical methods relevant to engineering and the physical, biological, and social sciences. The department offers honors courses in both Linear Algebra and Calculus III (110.211-212). Additional courses oriented toward applications include 110.311, 110.417, 110.421 and 110.443. Students interested in the theoretical foundations of mathematics may select 110.401-402, 110.405-406, 110.413, and 110.439. Students planning to pursue further study in mathematics should work toward taking these theoretical courses as early as possible in their undergraduate years and are encouraged to take graduate-level courses as soon as they are qualified.

Requirements for the B.A. Degree:

In addition to the General Requirements for Departmental Majors, a candidate for the bachelor's degree in Mathematics is required to have credit for the courses listed below. All courses used to meet these requirements must be completed with a grade of C- or better. Honors Calculus III and Honors Linear Algebra (110.211-212) can be used in place of Calculus III and one course as described below.

- Calculus I, II, and III.
- 110.401 and one other term of algebra, either 110.204 or 110.402. (110.201 Linear Algebra does not satisfy this requirement.)
- 110.405 and one other term of analysis chosen from 110.311, 110.406, 110.417,
- 110.421, 110.439, and 110.443.
- Two terms of courses chosen from 110.201, 110.204, and mathematics courses at the 300-level or above. 110.211-212 Honors Calculus III and Linear Algebra may be used in place of Calculus III and one course in this requirement.
- Two terms in any one of the following areas of applications of mathematics, or other appropriate advanced courses as approved by the Director of Undergraduate Studies.
- Physics and Chemistry: 171.204, 301-302, 303-304, 312; 030.453.
Probability and Statistics: 550.420, 426, 430, 620, 630.
Applied Mathematics & Statistics: 550.361-362, 471, 472, 681.
Economics: 180.301, 302, 311.
Computer Science: 600.226, 435 and three credit courses numbered 605.425 and higher.

Requirements for a Minor in Mathematics:

Students with a major in another department may be awarded a minor in mathematics upon completion of satisfactory work in the following courses:

- Calculus I, II, and III.
- Four mathematics courses at the 200-level or above (excluding Calculus III), of which at least three are at the 300-level. A course in the Applied Mathematics and Statistics Department (at the corresponding level) may be substituted for one of the four courses.
- All courses used to meet these requirements must be completed with a grade of C- or better.

Honors Program in Mathematics:

As a general guideline, departmental honors are awarded to recipients of the B.A. degree who have completed Complex Analysis 110.311, as well as

12 cr
9
miss
9
9 + 110.421
= 13.5 cr
49.5
07
46

the Algebra sequence 110.401-402, the Real Analysis sequence 110.405-406, and one more course at the 400 level or above with at least a 3.6 average in these six courses.

J. J. Sylvester Prize

The J. J. Sylvester Prize in Mathematics, which carries a cash award, is given each year to an outstanding graduating senior majoring in mathematics.

The B.A./M.A. Program

By applying the same courses simultaneously toward the requirements for the B.A. and M.A. degrees, an advanced student can qualify for both degrees in four years. Admission to the program is by the standard graduate application form, which should be completed in the junior year. Students may contact the graduate program assistant for further information.

For candidates for the B.A./M.A. degree, at least a 3.0 average is required in the 400-level mathematics courses taken while resident at the university.

Graduate Programs

Admission

Admission to the Ph.D. program is based on academic records, letters of recommendation, and Graduate Record Examination scores. International applicants are required to submit a TOEFL score if English is not their native language.

Basic Program

Graduate study in mathematics is centered around 10 basic courses: 110.601-602, 110.605-606, 110.607-608, 110.611-612, 110.615-616, 110.617-618, 110.619-620, 110.631-632, 110.643-644, and 110.645-646. These courses are preliminary to research. The 700-level courses are designed to bring students abreast of recent developments and to prepare them for research in the area of their choice.

The basic graduate courses are built upon the foundations constituted by the 400-level courses 110.401-402, 110.405-406, and 110.413.

Requirements for the M.A. Degree:

- Completion, while resident at the university, of one basic graduate sequence, 110.601-602, 110.605-607, and demonstration of a deeper understanding by passing one written qualifying examination.

- A reading knowledge of French, German, or Russian, to be demonstrated by passing an examination given in the Department of Mathematics.

Requirements for the Ph.D. Degree:

- Satisfactory work in the analysis sequence 605 (Real Analysis I) and 607 (Complex Variables I) as well as the Algebra Sequence 601-602. Enrollment in these two sequences is mandatory for all first year graduate students unless they have received advanced placement by passing the corresponding written qualifying exam(s).
- Passing written qualifying exams by September of the second year in:
 1. Analysis (Real and Complex)
 2. Algebra
- Satisfactory work in at least three other 600-level courses in the second year of study.
- A reading knowledge of French, German, or Russian, to be demonstrated by passing an examination given in the Department of Mathematics.
- Passing an oral qualifying examination in the students chosen area of research. The topics on the exam are to be chosen in consultation with a faculty member (normally the student's future thesis adviser). This must be done by March of the third year.
- Some teaching of mathematics, usually at the undergraduate level, under the supervision of a faculty member.
- A written dissertation based upon independent research.
- The final Graduate Board oral examination, which is the dissertation defense.

Financial Aid

Most students admitted to the Ph.D. program receive teaching assistantships and full tuition fellowships. Exceptional applicants become candidates for one of the university's George E. Owen Fellowships, which carry no required duties the first year.

William Kelso Morrill Award

The William Kelso Morrill Award for excellence in the teaching of mathematics is awarded every spring to the graduate student who best exemplifies the traits of Kelso Morrill: a love of mathematics, a love of teaching, and a concern for students.

Undergrad

- Please visit the jhu.edu for updates
- Any course presented with a grade of C

110.105 (Q) Intro
This course starts from all the background it includes a review of differential and logarithmic functions. Each of these tools is presented in a historical context. A function will be introduced and its properties will be studied. 4 credits

110.106-107 (Q) Calculus (Sciences)
Differential and integral calculus, function introduction to differential variables, line integral, differential equations. (Many applications will be discussed.) 4 credits

110.108-109 (Q) Calculus (Engineering)
Differential and integral calculus, functions, coordinates, parametric equations, applications, inflections to the parabola, and the study of students in the field. 4 credits

110.113 (Q) Honors
This is an honors level requirement: treatment of one of our modern and explained by Car who want to know find this course already understood differentiation, change and will learn about mental theorem, and Taylor in Calculus I, with "A" in 110.106. 4 credits

110.201 (Q) Linear
Vector spaces, linear transformations of systems.

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Undergraduate Courses

- Please visit the Mathematics web page at www.math.jhu.edu for updated course offerings.
- Any course presented as a prerequisite must be completed with a grade of C- or higher

110.105 (Q) Introduction to Calculus

This course starts from scratch and provides students with all the background necessary for the study of calculus. It includes a review of algebra, trigonometry, exponential and logarithmic functions, coordinates and graphs. Each of these tools will be introduced in its cultural and historical context. The concept of the rate of change of a function will be introduced. Not open to students who have studied calculus in high school.
4 credits

110.106-107 (Q) Calculus I, II (Biological and Social Sciences)

Differential and integral calculus. Includes analytic geometry, functions, limits, integrals and derivatives, introduction to differential equations, functions of several variables, linear systems, applications for systems of linear differential equations, probability distributions. (Many applications to the biological and social sciences will be discussed.)
4 credits

110.108-109 (Q) Calculus I, II (Physical Sciences and Engineering)

Differential and integral calculus. Includes analytic geometry, functions, limits, integrals and derivatives, polar coordinates, parametric equations, Taylor's theorem and applications, infinite sequences and series. (Some applications to the physical sciences and engineering will be discussed, and the courses are designed to meet the needs of students in these disciplines.)
4 credits

110.113 (Q) Honors Calculus II

This is an honors alternative to 107 or 109 and meets general requirement for Calculus 2. It is a more theoretical treatment of one variable integral calculus and is based on our modern understanding of the real number system as explained by Cantor, Dedekind, and Weierstrass. Students who want to know the "why's and how's" of Calculus will find this course rewarding. Students will be expected to already understand differential calculus (derivatives, differentiation, chain rule, optimization, related rates, etc), and will learn about the theory of integration, the fundamental theorem(s) of Calculus, applications of integration, and Taylor series. Prerequisite: A strong background in Calculus I, such as a 5 on the AP/BC Calculus exam, an "A" in 110.106 or 110.108.
4 credits

110.201 (Q) Linear Algebra

Vector spaces, matrices, and linear transformations. Solutions of systems of linear equations. Eigenvalues, eigen-

vectors, and diagonalization of matrices. Applications to differential equations. Prerequisite: Calculus I.
4 credits

110.202 (Q) Calculus III (Calculus of Several Variables)

Calculus of functions of more than one variable: partial derivatives and applications; multiple integrals, line and surface integrals; Greens Theorem, Stokes Theorem, and Gauss Divergence Theorem. Prerequisite: Calculus II.
4 credits

110.204 (Q) Elementary Number Theory

The student is provided with many historical examples of topics each of which serves as an illustration of and provides a background for many years of current research in number theory. This course also provides the student with concrete examples of general abstract concepts studied in 110.401-402. Primes and prime factorization, congruences, Eulers function, quadratic reciprocity, primitive roots, solutions to polynomial congruences (Chevalley's theorem), Diophantine equations including the Pythagorean and Pell equations, Gaussian integers, Dirichlet's theorem on primes. Prerequisite: Calculus I.
4 credits

110.211 (Q) Honors Calculus III

This course includes the material in Calculus III (202) with some additional applications and theory. Recommended for mathematically able students majoring in physical science, engineering, or especially mathematics. 211-212 used to be an integrated year-long course, but now the two are independent courses and can be taken in either order. Prerequisite: B+ or better in Calculus II, or 5 on the Calculus BC AP Exam.
4 credits

110.212 (Q) Honors Linear Algebra

This course includes the material in Linear Algebra (201) with some additional applications and theory. Recommended for mathematically able students majoring in physical science, engineering, or mathematics. 211-212 used to be an integrated year-long course, but now the two are independent courses and can be taken in either order. This course satisfies a requirement for the math major that its non-honors sibling does not. Prerequisite: Calculus II or III or equivalent, preferably honors.
4 credits

110.225 (Q) Putman Problem Solving

Problem solving course to prepare students for the Putman exam.
3 credits

110.228 (Q) Non-Euclidean Geometry

For 2,000 years, Euclidean geometry was the geometry. In the 19th century, new, equally consistent but very different geometries were discovered. This course will delve

into these geometries on an elementary but mathematically rigorous level. Prerequisite: high school geometry. 3 credits

110.302 (Q,E) Differential Equations with Applications

This is an applied course in ordinary differential equations, which is primarily for students in the biological, physical and social sciences, and engineering. The purpose of the course is to familiarize the student with the techniques of solving ordinary differential equations. The specific subjects to be covered include first order differential equations, second order linear differential equations, applications to electric circuits, oscillation of solutions, power series solutions, systems of linear differential equations, autonomous systems, Laplace transforms and linear differential equations, mathematical models (e.g., in the sciences or economics). Prerequisite: Calculus II. 4 credits

110.311 (Q) Methods of Complex Analysis

This course is an introduction to the theory of functions of one complex variable. Its emphasis is on techniques and applications, and it serves as a basis for more advanced courses. Functions of a complex variable and their derivatives; power series and Laurent expansions; Cauchy integral theorem and formula; calculus of residues and contour integrals; harmonic functions. Prerequisite: Calculus III. 4.5 credits

110.345 Basics Notions in Mathematics

This seminar course is intended to introduce majors and those interested in mathematics to a large collection of topics that they may not have seen before. It meets weekly with a different speaker each week. Prerequisites: Significant experience (at least two courses) with mathematics at the 200-level or above. 1 credit

110.401 (Q) Advanced Algebra I

An introduction to the basic notions of modern algebra. Elements of group theory: groups, subgroups, normal subgroups, quotients, homomorphisms. Generators and relations, free groups, products, commutative (Abelian) groups, finite groups. Groups acting on sets, the Sylow theorems. Definition and examples of rings and ideals. Introduction to field theory. Linear algebra over a field. Field extensions, constructible polygons, non-trisectability. Prerequisite: Linear Algebra. 4.5 credits

110.402 (Q) Advanced Algebra II

This is a continuation of 110.401. Theory of fields (continued). Splitting field of a polynomial, algebraic closure of a field. Galois theory: correspondence between subgroups and subfields. Solvability of polynomial equations by radicals. Modules over a ring. Principal ideal domains, structure of finitely generated modules over them. Applications. 4.5 credits

110.405 (Q) Analysis I

This course is designed to give a firm grounding in the basic tools of analysis. It is recommended as preparation (but may not be a prerequisite) for other advanced analysis courses. Real and complex number systems, topology of metric spaces, limits, continuity, infinite sequences and series, differentiation, Riemann-Stieltjes integration. Prerequisites: Calculus III, Linear Algebra. 4.5 credits

110.406 (Q) Analysis II

This course continues 110.405, with an emphasis on the fundamental notions of modern analysis. Sequences and series of functions, Fourier series, equicontinuity and the Arzela-Ascoli theorem, the Stone-Weierstrass theorem. Functions of several variables, the inverse and implicit function theorems, introduction to the Lebesgue integral. Prerequisite: 110.405. 4.5 credits

110.407-408 (Q,N) Geometry and Relativity

Special relativity: Lorentz transformation, Minkowski spacetime, mass, energy-momentum, stress-energy tensor, electrodynamics. Introduction to differential geometry: theory of surfaces, first and second fundamental forms, curvature, Gauss's theorem egregium, differentiable manifolds, connections and covariant differentiation, geodesics, differential forms, Stokes theorem. Gravitation as a geometric theory: Lorentz metrics, Riemann curvature tensor, tidal forces and geodesic deviation, gravitational redshift, Einstein field equation, the Schwarzschild solution, perihelion precession, the deflection of light, black holes, cosmology. Prerequisites: Calculus II, Linear Algebra, General Physics II. 4.5 credits

110.409 (Q) Introduction to Algebraic Number Theory

This is an introduction to the arithmetic of rings of algebraic integers and more general Dedekind domains. It covers topics such as the unique factorization theorem for ideals in rings of algebraic integers, integral bases, the discriminant, the different, ramification, the finiteness theorem for ideal-class groups, Dirichlet's theorem on groups of units of rings of algebraic integers, etc. Prerequisites: Algebra 110.401-402. 4 credits

110.411 (Q) Honors Complex Analysis

Study of functions of a complex variable, emphasis on interrelations with other parts of mathematics. Topics include Cauchy's theorems, singularities, gamma and zeta functions, elliptic functions, theta functions, Jacobi's triple product. Prerequisite: Calculus III, Linear Algebra. 4.5 credits

110.413 (Q) Introduction to Topology

The basic concepts of point-set topology: topological spaces, connectedness, compactness, quotient spaces, metric spaces, function spaces. An introduction to algebraic topology: covering spaces, the fundamental group, and other topics as time permits. Prerequisite: Calculus III. 4.5 credits

110.415 (Q) Honors
This highly theoretical course is designed for the most able students in the number system, the Lebesgue integral, Calculus III and I. 4.5 credits

110.417 (Q,E) Partial Differential Equations
Characteristics, well-posed problems, Poisson's equation and dependence and dependence formula, maximum principle, Dirichlet problems. The maximum principle. Prerequisite: 110.401. 4.5 credits

110.423 (Q) Lie Groups
This course is a representation theory of Lie groups. It covers basic Lie groups and their representations. It is useful for students interested in group representation theory. Prerequisite: Some group theory. 4 credits

110.427 (Q) Integral Equations
The calculus of variations, integral equations, integral invariants, constraints. Invariant measures on geometric phase space with active parameters as reparametrizations of curves and surfaces. Prerequisites: Calculus III. 4 credits

110.429 (Q) Mathematical Physics
The basis of quantum mechanics. The focus is on the Schrodinger equation, bound states, uncertainty principle. Prerequisite: 110.302 (Differential Equations). 4 credits

110.415 (Q) Honors Analysis I

This highly theoretical sequence in analysis is reserved for the most able students. The sequence covers the real number system, metric spaces, basic functional analysis, the Lebesgue integral, and other topics. Prerequisites: Calculus III and Linear Algebra.
4.5 credits

110.417 (Q,E) Partial Differential Equations for Applications

Characteristics, classification of second order equations, well-posed problems, separation of variables and expansions of solutions. The wave equation: Cauchy problem, Poissons solution, energy inequalities, domains of influence and dependence. Laplaces equation: Poissons formula, maximum principles, Greens functions, potential theory, Dirichlet and Neumann problems, eigenvalue problems. The heat equation: fundamental solutions, maximum principles. Prerequisites: Calculus III. Recommended: 110.405.
4.5 credits

110.423 (Q) Lie Groups for Undergraduates

This course is an introduction to Lie Groups and their representations at the upper undergraduate level. It will cover basic Lie groups such as $SU(2)$, $U(n)$, the Euclidean Motion Group and the Lorentz Group. This course is useful for students who want a working knowledge of group representations. We will also discuss some aspects of the role of symmetry groups in particle physics such as some of the formal aspects of the electroweak and the strong interactions. A good reference is the book *Lie Algebras in Particle Physics* by Howard Georgi. Prerequisite: Some group theory would be helpful.
4 credits

110.427 (Q) Introduction to the Calculus of Variations

The calculus of variations is concerned with finding optimal solutions (shapes, functions, etc.) where optimality is measured by minimizing a functional (usually an integral involving the unknown functions) possibly with constraints. In this introductory (self-contained) course, we will concern ourselves with one dimensional (often geometric) problems: brachistochrone, geodesics, minimum surface area of revolution, isoperimetric problem, curvature flows. We will run the course in a seminar style with active participation required. I will teach additional material as required (some differential geometry of curves and surfaces) to hold prerequisites to a minimum. Prerequisites: Calculus I, II, III.
4 credits

110.429 (Q) Mathematics of Quantum Mechanics

The basis of quantum mechanics is the Schrodinger equation. The focus of this course will be on one-dimensional Schrodinger equations. Topics include eigenvalue problems, bound states, scattering states, tunneling, uncertainty principle, dynamics, semi-classical limit. The ideas will be illustrated through many examples. Prerequisite: 110.302 (Differential Equations with Applications) or permission of the instructor.
4 credits

110.431 (Q) Introduction to Knot Theory

The theory of knots and links is a royal road to modern topology. The prerequisite for this course is a good grade in Calculus III, but the material will be mathematically sophisticated, and some familiarity with the notion of group would be helpful. We will start with braids, and work up to knots and links. The fundamental group of a knot or link complement will be the central algebraic focus, and spanning surfaces will be the main geometric tool. Together these lead very intuitively to homology groups (in low dimensions).
4 credits

110.439 (Q) Introduction to Differential Geometry

Theory of curves and surfaces in Euclidean space: Frenet equations, fundamental forms, curvatures of a surface, theorems of Gauss and Mainardi-Codazzi, curves on a surface; introduction to tensor analysis and Riemannian geometry; theorem egregium; elementary global theorems. Prerequisites: Calculus III, Linear Algebra.
4.5 credits

110.443 (Q,E) Fourier Analysis and Generalized Functions

An introduction to the Fourier transform and the construction of fundamental solutions of linear partial differential equations. Homogeneous distributions on the real line: the Dirac delta function, the Heaviside step function. Operations with distributions: convolution, differentiation, Fourier transform. Construction of fundamental solutions of the wave, heat, Laplace and Schrödinger equations. Singularities of fundamental solutions and their physical interpretations (e.g., wave fronts). Fourier analysis of singularities, oscillatory integrals, method of stationary phase. Prerequisites: Calculus III, Linear Algebra. Recommended: 110.405.
4.5 credits

110.462 (Q) Prime Numbers and Riemann's Zeta Function

This course is devoted to such questions as: How many prime numbers are there less than N ? How are they spaced apart? Although prime numbers at first sight have nothing to do with complex numbers, the answers to these questions (due to Gauss, Riemann, Hadamard) involve complex analysis and in particular the Riemann zeta function. The best known unsolved conjecture in mathematics is about the zeros of Riemann zeta function, which control the distribution of primes. This course builds on 110.311 (Complex Analysis) and is an introduction to Analytic Number Theory for undergraduates. Prerequisite: 110.311.
4 credits

110.472 (Q) Differential Topology

Topics include manifolds, tangent spaces, immersions, submersions, transversality, intersection theory modulo 2, intersection numbers in the integers and Lefschetz fixed point theorem, and integration of differential forms on manifolds. Prerequisites: Calculus III and either 110.405 or 110.413.
4.5 credits