Washington University in St. Louis

Mathematics

Mathematics has always held a central position in the liberal arts, and over time it has also come to play an important role in more and more aspects of our lives. Mathematical analysis and modeling are involved in many areas, far beyond the traditional association of mathematics with the physical sciences and engineering. This fact is reflected in the diversity of the students who study at least some mathematics during their time at Washington University — students who recognize the importance of quantitative skills in a world that becomes more and more technological.

Students major in mathematics for many reasons. Some are planning academic careers in mathematics or statistics that involve teaching or research. Others plan to work as actuaries or at other jobs in industry or government. Some plan careers in secondary education. Many majors do not intend to become "mathematicians" at all, but simply realize that quantitative training is a valuable asset in many kinds of careers; often, work in mathematics or statistics is meant to complement their study in other areas. Still other majors just view mathematics as an interesting concentration in their liberal arts education, even though they plan to enter professional fields such as medicine or law.

The Mathematics program gives majors and minors a broad introduction to the subject. Majors choose among several tracks to complete their study; these tracks add different emphases to their programs, reflecting individual interests or professional goals. Majors are encouraged to complete additional work (perhaps even a minor or second major) in other related areas.

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Faculty

Chair

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Spencer T. Olin Professor of Mathematics
PhD, University of California, Berkeley
Analysis; operator theory; one and several complex variables

Directors

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PhD, Brown University
Complex analysis, harmonic analysis, operator theory, and several complex variables

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Algebraic and topological combinatorics

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Undergraduate Mathematics Education

Majors

The Major in Mathematics

Total units required: 36-39

All mathematics majors are required to complete

Code	Title	Units
Math 131	Calculus I	3
Math 132	Calculus II	3
Math 233	Calculus III	3
Total Units		9

In addition, each major is required to complete the courses
in one of the following five tracks and to participate in a
departmental exit interview shortly before graduation.

Traditional

Code	Title	Units
Math 3200	Elementary to Intermediate Statistics and Data Analysis	3
or Math 493	Probability	
Math 310	Foundations for Higher Mathematics	3
Math 4111 & Math 4121	Introduction to Analysis and Introduction to Lebesgue Integration	6
Math 429 & Math 430	Linear Algebra and Modern Algebra	6
Three additional upper-level mathematics electives. Two of these could be Math 309 and Math 318 (or Math 308). At least one elective must be at the 400 level.		9

Total 27 upper-level mathematics units

Probability/Statistics

Code	Title	Units
One course in computer science chosen from CSE 131, CSE 132, CSE 200, CSE 247		3
Math 309	Matrix Algebra	3
Math 3200	Elementary to Intermediate Statistics and Data Analysis	3
Math 310	Foundations for Higher Mathematics	3
Math 318	Introduction to Calculus of Several Variables	3
or Math 308	Mathematics for the Physical Sciences	
Math 493 & Math 494	Probability and Mathematical Statistics	6
Two additional upper-level mathematics electives in the areas of probability or statistics		6

Total 24 upper-level mathematics units

Applied

Code	Title	Units
One course in computer science chosen from CSE 131, CSE 132, CSE 200, CSE 247		3
Math 217	Differential Equations	3
Math 309	Matrix Algebra	3
Math 3200	Elementary to Intermediate Statistics and Data Analysis	3
or Math 493	Probability	
Math 310	Foundations for Higher Mathematics	3
Math 318	Introduction to Calculus of Several Variables	3
or Math 308	Mathematics for the Physical Sciences	
Math 449 & Math 450	Numerical Applied Mathematics and Topics in Applied Mathematics	6
Two additional upper-level mathematics electives. Major track must include at least one of Math 410, Math 415, Math 416, or Math 4111.		6

Total 24 upper-level mathematics units

Mathematics for Secondary Education

(This track also requires a major in secondary education)

Code	Title	Units
One course in computer science chosen from CSE 131, CSE 132, CSE 200, CSE 247		3
Math 309	Matrix Algebra	3
Math 3200	Elementary to Intermediate Statistics and Data Analysis	3
or Math 493	Probability	
Math 310	Foundations for Higher Mathematics	3

Math 318	Introduction to Calculus of Several Variables	3
or Math 308	Mathematics for the Physical Sciences	
Math 302	Elementary Geometry From an Advanced Point of View	3
Math 331	Algebraic Systems	3
Two additional upper-level mathematics electives		6

Total 24 upper-level mathematics units

Mathematics (Economics Emphasis)

Three economics courses:

Code	Title	Units
Econ 1011 and Econ 1021		6
One Economics course chosen from among Econ 4011, Econ 4151, or Econ 467		3

and

Code	Title	Units
Math 309	Matrix Algebra	3
Math 3200	Elementary to Intermediate Statistics and Data Analysis	3
or Math 493	Probability	
Math 310	Foundations for Higher Mathematics	3
Math 4111 & Math 4121	Introduction to Analysis and Introduction to Lebesgue Integration	6
Three additional upper-level courses from among Math 318, Math 429, Math 456, or any 400-level probability or statistics course. The major must include at least one of Math 493 or Math 429.		9

Total 24 upper-level mathematics units + 3 upper-level economics units

Notes applying to all major tracks

1. Students who entered Washington University before fall 2015 should visit the Prior Bulletins (http://bulletin.wustl.edu/prior) section of this *Bulletin* to view the major requirements that were in place for the appropriate year of matriculation. These requirements can also be found from the department's undergraduate webpage (http://wumath.wustl.edu/undergraduate/information-math-majors/five-major-tracks).

2. Upper-level mathematics courses are those whose course number begins with a "3" or higher; e.g., Math 3***. Lower-level courses do not count toward upper-level mathematics requirements even if cross-listed as an upper-level course in another department or program. For example, if Math 2200 were cross-listed by another department as 3***, then registering for that 3*** course would not satisfy an upper-level mathematics requirement.

3. All required courses (lower- and upper-level) must be completed with a grade of C- or better.

4. Math 318 Introduction to Calculus of Several Variables and Math 308 Mathematics for the Physical Sciences cannot both be used to fulfill major requirements.

5. Courses transferred from other accredited colleges and universities with department approval can be counted. However,
   a. courses transferred from a two-year college (such as a community college) cannot be used to satisfy upper-level requirements;
   b. at least half the upper-level units required in a major must be earned at Washington University or in a Washington University-approved Overseas Study program;
   c. courses from University College cannot be used to fulfill major requirements.

6. At most 3 units for independent study or research work can count toward the major requirements.

7. No upper-level course used to satisfy a major requirement can be counted toward the requirements of any other major or minor (no "double-counting").

8. Certain approved substitutions are found on the department's webpage (http://wumath.wustl.edu/fall15classfive-major-tracks). However, in all cases, at most one substitution can be used that involves a course not home-based in the Department of Mathematics.

Additional Information

Independent Study: Majors with a plan for independent work or a research project may apply for independent study with a faculty member. Majors are encouraged (but not required) to consider a senior project or an honors project.

Graduation with Awards for Distinction or Latin Honors: The department offers the awards Distinction in Mathematics, High Distinction in Mathematics, and Highest Distinction in Mathematics. Recommendations for students to receive Latin Honors (which are awarded by the College of Arts & Sciences, not the department) are keyed to the requirements for the Distinction Awards, as indicated below. In these requirements, "regularly scheduled mathematics course" refers to a course that is home-based in the mathematics department (L24) and is not an independent study or research course.

- Core Course Work for All Distinction Awards (Core Course Work alone earns no award)

   a) at least 3.65 GPA in upper-level mathematics (L24) courses

   b) completion with grades of B or better (not B-) of

      i) one of the course sequences Math 4111-4121, 429-430, 493-494, 449-450, and

ii) three additional regularly-scheduled 400-500 level mathematics courses

- Distinction in Mathematics. Awarded for Core Course Work <u>plus</u>

  a) completion of one additional regularly-scheduled mathematics course at the 400-500 level with grade of B or better (not B-), **or**

  b) passing the first actuarial exam (Exam P) from Society of Actuaries

- High Distinction in Mathematics. Awarded for Core Course Work <u>plus</u> satisfactory completion of an honors thesis. Details about honors theses (http://wumath.wustl.edu/undergraduate/information-math-majors/distinction-and-latin-honors/requirements-and-suggestions) are available on the department's webpage.

- Highest Distinction in Mathematics. Awarded for Core Course Work <u>plus</u> satisfactory completion of an honors thesis <u>plus</u> one of the following:

  a) course work includes completion of at least one of the graduate sequences Math 5021-5022, 5031-5032, 5041-5042(3), 5051-5052, 5061-5062 and passing the graduate qualifying exam for that course sequence, <u>or</u>

  b) course work includes all the requirements for the department's Honors Program in Statistics (http://wumath.wustl.edu/undergraduate/information-math-majors/honors-program-statistics)

- Latin Honors. For majors in the College of Arts & Sciences, the department will recommend that the AB degree be awarded with Latin Honors if the student has an <u>overall</u> GPA of 3.65, as required by the college, and has earned the department award of High or Highest Distinction. These majors must apply to the department for admission to Candidacy for Latin Honors by the end of their junior year. The level of Latin Honors (cum laude, magna cum laude or summa cum laude) is determined by the college as described in the Arts & Sciences Academic Honors & Awards (http://bulletin.wustl.edu/undergrad/artsci/honors) section of this *Bulletin*.

More details are available on the department's webpage (http://wumath.wustl.edu).

Study Abroad: Students interested in a semester or year abroad studying mathematics intensively should consider the Budapest Semesters in Mathematics Program (http://www.budapestsemesters.com).

Minors
The Minor in Mathematics

Units required: 24

Required courses:

Code	Title	Units
One course in computer science chosen from CSE 131, CSE 132, CSE 200, CSE 247		3
Math 131	Calculus I	3
Math 132	Calculus II	3
Math 233	Calculus III	3
Math 309	Matrix Algebra	3
Math 318	Introduction to Calculus of Several Variables	3
or Math 308	Mathematics for the Physical Sciences	
Math 3200	Elementary to Intermediate Statistics and Data Analysis	3
or Math 493	Probability	
One additional upper-level (300- or 400-level) elective		3
Total Units		24

Additional Information

1. Students who entered Washington University <u>before fall 2015</u> should visit the Prior Bulletins (http://bulletin.wustl.edu/prior) section of this *Bulletin* to view the minor requirements that were in place for the appropriate year of matriculation. These requirements can also be found from the department's undergraduate webpage (http://wumath.wustl.edu/undergraduate-new/information-minors).

2. All required courses (lower- and upper-level) must be completed with a letter grade of C- or better.

3. Math 318 and Math 308 cannot both be used to fulfill minor requirements.

4. Courses transferred from other accredited colleges and universities with department approval can be counted. However,
   a. courses transferred from a two-year college (such as a community college) cannot be used to satisfy upper-level requirements;
   b. at least 6 of the upper-level units required in a minor must be earned at Washington University or in a Washington University-approved Overseas Study Program;
   c. courses from University College cannot be used to fulfill major requirements.

5. No <u>upper-level</u> course used to satisfy a minor requirement can be counted toward the requirements of any other major or minor (no "double-counting").

6. At least three of the four upper-level courses required in the minor must be courses "home-based" in the math department. One approved course from another department may be substituted. Approved substitutions can be found on the department webpage (http://wumath.wustl.edu/undergraduate-new/information-minors).

Courses

Visit online course listings to view semester offerings for L24 Math (https://courses.wustl.edu/CourseInfo.aspx?sch=L&dept=L24&crslvl=1:4).

L24 Math 100 Foundations for Calculus
A limited enrollment class for students planning to take calculus but who need additional precalculus preparation. The course aims to build both the technical skills and the conceptual understanding needed to succeed in calculus. Course emphasizes links between the graphical, numeric and algebraic viewpoints. A variety of approaches are used to present the material. Prerequisites: two years of high school algebra and a course in geometry (or the equivalent).
Credit 3 units. A&S: NS A&S IQ: NSM

L24 Math 1011 Introduction to Statistics
Basic concepts of statistics. Data collection (sampling, designing experiments), data organization (tables, graphs, frequency distributions, numerical summarization of data), statistical inference (elementary probability and hypothesis testing). Prerequisite: two years of high school algebra.
Credit 3 units. A&S: NS, QA A&S IQ: NSM, AN Arch: NSM Art: NSM

L24 Math 109 Mathematics and Music
An elementary introduction to the connections between mathematics and musical sound. Review of integers, ratios, prime numbers, functions, rationality, exponents, logarithms, trigonometry. Review of scales, clefs, key signatures, intervals, time signatures. Frequency and pitch. The connection between intervals and logarithms. Tuning and temperament, just intonation. Scales and modular arithmetic. The mathematics of harmony; the sound of the low prime numbers and their roles in harmony. Harmonics, partials and overtones. Numerical integration and basic Fourier analysis. The nature of complex tones. Analysis of instrument sounds. Human vowels and formants. Prerequisites: two years of high school algebra, and trigonometry.
Credit 3 units. A&S: NS, QA A&S IQ: NSM, AN Arch: NSM Art: NSM

L24 Math 131 Calculus I
Derivatives of algebraic, trigonometric and transcendental functions, techniques of differentiation, Mean Value Theorem, applications of the derivative. The definite integral and Fundamental Theorem of Calculus. Areas. Simpler integration techniques. Prerequisites: high-school algebra and precalculus, including trigonometry.
Credit 3 units. A&S: NS, QA A&S IQ: NSM, AN Art: NSM

L24 Math 132 Calculus II
Continuation of Math 131. A brief review of the definite integral and Fundamental Theorem of Calculus. Techniques of integration, applications of the integral, sequences and series, Taylor polynomials and series, and some material on differential equations. Prerequisite: Math 131 or a B or better in a one-year high school calculus course, or permission of the department.
Credit 3 units. A&S: NS, QA A&S IQ: NSM, AN Art: NSM

L24 Math 139A Real Mathematical Applications: Solving Problems with Calculus I
This is a 1-credit course that can only be taken concurrently with Math 131, Calculus I. The purpose of the course is to show how mathematics can solve real-world problems, and how calculus dramatically expands the range of problems that can be tackled. Each class will be devoted to the analysis of some problems, which may include: dimensional analysis, the mathematics of convoys, Fibonacci numbers, fractals, linear regression, Euclid's algorithm, Stein's algorithm, network capacities, Braess' paradox, Galton's approach to surnames, how genes spread through populations, SIR model of infectious diseases. The first few classes will not use differentiation. Must be taken concurrently with Math 131.
Credit 1 unit. Arch: NSM Art: NSM

L24 Math 203 Honors Mathematics I
This is the first half of a one-year calculus sequence for first year students with a strong interest in mathematics with an emphasis on rigor and proofs. The course begins at the beginning but assumes the students have already studied the material from a more "mechanical" view. Students who complete both semesters will have completed the material Calc III and other topics that may let them move through the upper-level math curriculum more quickly. Sets, functions, real numbers, and methods of proof. The Riemann-Darboux integral, limits and continuity, differentiation, and the fundamental theorems of calculus. Sequences and series of real numbers and of functions. Vector spaces and linear maps. Prerequisite: Score of 5 on the AP Calculus Exam, BC version, or the equivalent.
Credit 4 units. A&S: NS, QA A&S IQ: NSM, AN

L24 Math 204 Honors Mathematics II
Matrices, linear systems, and determinants. Eigenvalues and eigenvectors, diagonalization, and the spectral theorem. Scalar and vector fields, differential and integral calculus of several variables, and the fundamental theorems of Green, Gauss, and Stokes. Restricted to first year students who have completed Math 203 in the fall semester. Math 204 can replace Math 233 in major/minor requirements.
Credit 4 units. A&S: NS, QA A&S IQ: NSM, AN Art: NSM

L24 Math 217 Differential Equations
Introduction to ordinary differential equations: first-order equations, linear equations, systems of equations, series solutions, Laplace transform methods, numerical solutions. Prerequisite: Math 233 (or Math 233 concurrently).
Credit 3 units. A&S: NS, QA A&S IQ: NSM, AN Art: NSM

L24 Math 220 Finite Mathematics
Topics selected from number theory, combinatorics and graph theory. Methods of proof and practical applications: for example, calendars, scheduling, communications, encryption. Prerequisite: high school algebra.
Credit 3 units. A&S: NS, QA A&S IQ: NSM, AN Art: NSM

L24 Math 2200 Elementary Probability and Statistics
An introduction to probability and statistics. Discrete and continuous random variables, mean and variance, hypothesis testing and confidence limits, nonparametric methods, Student's t, analysis of variance, regression and contingency tables. Graphing calculator with statistical distribution functions (such as the TI-83) may be required. Prerequisite: Math 131.

Credit 3 units. A&S: NS, QA A&S IQ: NSM, AN Arch: NSM Art: NSM

L24 Math 233 Calculus III

Multivariable calculus. Topics include differential and integral calculus of functions of two or three variables: vectors and curves in space, partial derivatives, multiple integrals, line integrals, vector calculus at least through Green's Theorem. Prerequisite: Math 132 or a score of 4-5 on the Advanced Placement Calculus Exam (BC version).
Credit 3 units. A&S: NS, QA A&S IQ: NSM, AN Art: NSM

L24 Math 266 Math for Elementary School Teachers

A review of elementary school mathematics at a level beyond its usual presentation in the schools. Applications of all concepts are given in abundance. Restricted to majors in Elementary Education. Prerequisite: two years of high school mathematics.
Credit 3 units. A&S: NS, QA A&S IQ: NSM, AN Art: NSM

L24 Math 302 Elementary Geometry From an Advanced Point of View

A rigorous modern treatment of Euclidean geometry and an introduction to non-Euclidean geometry. Prerequisite: Math 310 or permission of instructor.
Credit 3 units. A&S: NS A&S IQ: NSM Arch: NSM Art: NSM

L24 Math 308 Mathematics for the Physical Sciences

Continuation of Math 233 emphasizing topics of interest in the physical sciences. Topics in multivariable and vector calculus (div, grad, curl); line, surface integrals and connections to electromagnetism; Fourier series and integrals; boundary value problems (diffusion and wave equations); additional topics if time permits. Students may not receive credit toward a math major or minor for both Math 308 and Math 318. Prerequisite: Math 233 and 217, or permission of instructor.
Credit 3 units. A&S: NS A&S IQ: NSM Arch: NSM Art: NSM BU: SCI

L24 Math 309 Matrix Algebra

An introductory course in linear algebra that focuses on Euclidean n-space, matrices and related computations. Topics include: systems of linear equations, row reduction, matrix operations, determinants, linear independence, dimension, rank, change of basis, diagonalization, eigenvalues, eigenvectors, orthogonality, symmetric matrices, least square approximation, quadratic forms. Introduction to abstract vector spaces. Prerequisite: Math 132.
Credit 3 units. A&S: NS, QA A&S IQ: NSM, AN Arch: NSM Art: NSM

L24 Math 310 Foundations for Higher Mathematics

Introduction to the rigorous techniques used in more advanced mathematics. Topics include postpositional logic, use of quantifiers, set theory, methods of proof and disproof (counterexamples), foundations of mathematics. Use of these tools in the construction of number systems and in other areas such as elementary number theory, combinatorial arguments and elementary proofs in analysis. Prerequisite: Math 233.
Credit 3 units. A&S: NS A&S IQ: NSM Art: NSM

L24 Math 310W Foundations for Higher Mathematics with Writing

Refer to the description for Math 310. Math 310W is a writing-intensive version of Math 310. Students participate in the regular Math 310 lectures and are responsible for all the exams and assignments associated with Math 310. Students in Math 310W have one additional meeting each week to deal with writing issues. At least three papers (four to five pages in length) are required, each with at least one revision. Prerequisite: Math 233 or permission of instructor.
Credit 4 units. A&S: NS, WI A&S IQ: NSM, WI

L24 Math 312 Differential Equations and Dynamical Systems

Qualitative theory of ordinary differential equations. Picard's existence and uniqueness theorem, the phase plane, Poincare-Bendixon theory, stationary points, attractors and repellors, graphical methods. Physical applications, including chaos, are indicated. Prerequisite: Math 217.
Credit 3 units. A&S: NS Art: NSM

L24 Math 318 Introduction to Calculus of Several Variables

Selected topics for functions of several variables involving some matrix algebra and presented at a level of rigor intermediate between that of Calculus III and higher-level analysis courses. Students may not receive credit toward a mathematics major or minor for both Math 308 and 318. Prerequisites: Math 233 and Math 309.
Credit 3 units. A&S: NS A&S IQ: NSM Art: NSM

L24 Math 3200 Elementary to Intermediate Statistics and Data Analysis

An introduction to probability and statistics. Discrete and continuous random variables, mean and variance, hypothesis testing and confidence limits, Bayesian inference, nonparametric methods, Student's t, contingency tables, multifactor analysis of variance, fixed effects, random effects, mixed models, multiple regression, maximum likelihood and logistic regression. Graphing calculator with Z, t, chi-square and F distribution functions (such as the TI-83 series) may be required. Calculus and the SAS software package are both used in an essential way. Prerequisite: Math 233 or permission of the instructor.
Credit 3 units. A&S: NS, QA A&S IQ: NSM, AN Arch: NSM Art: NSM

L24 Math 322 Biostatistics

A second course in elementary statistics with applications to life sciences and medicine. Review of basic statistics using biological and medical examples. New topics include incidence and prevalence, medical diagnosis, sensitivity and specificity, Bayes' rule, decision making, maximum likelihood, logistic regression, ROC curves and survival analysis. Prerequisites: Math 3200, or a strong performance in Math 2200 and permission of the instructor.
Credit 3 units. A&S: NS A&S IQ: NSM Art: NSM

L24 Math 331 Algebraic Systems

Polynomials, binomial expansions, factoring, rings (integers and polynomials), unique factorization, and other topics relevant to the high school curriculum. Designed for future secondary school teachers and other students looking for a course in algebra at a less abstract level than Math 430. Prerequisite: Math 310 or permission of instructor.

Credit 3 units. A&S: NS A&S IQ: NSM Art: NSM

L24 Math 3351 Elementary Theory of Numbers
Divisibility properties of integers, congruences, quadratic reciprocity, Diophantine equations. Introduction to continued fractions and a brief discussion of public key cryptography. Prerequisite: Math 310 or permission of instructor.
Credit 3 units. A&S: NS A&S IQ: NSM Art: NSM

L24 Math 350 Topics in Applied Mathematics
Topics change with each offering of the course. Past topics have included "Mathematics and Multimedia," "The Mathematics and Chemistry of Reaction-Diffusion Systems," "Mathematical Biology," and "Simulation Analysis of Random Processes" and "Introduction to Monte Carlo Methods." Prerequisites will vary but always include at least Math 233, Math 309 and basic programming skills in some language.
Credit 3 units. A&S: NS A&S IQ: NSM Art: NSM

L24 Math 370 Introduction to Combinatorics
Basics of enumeration (combinations, permutations and enumeration of functions between finite sets), generating functions; the inclusion-exclusion principle, partition theory and introductory graph theory. As time permits, additional topics may include Ramsey's Theorem, probabilistic methods in combinatorics and algebraic methods in combinatorics. Prerequisites: Math 132, 309 and 310, or permission of the instructor.
Credit 3 units. A&S: NS, QA A&S IQ: NSM, AN Arch: NSM Art: NSM

L24 Math 371 Graph Theory
Introduction to graph theory including the basic definitions and theorems and some more advanced topics that drive much current research in graph theory: Ramsey's Theorem, random graph theory and, if time permits, Szemeredi's regularity lemma. Graphs are studied as abstract objects; however, graph theory is also of interest to applied mathematicians because graphs are natural models for networks (social, electric). Prerequisite: Math 310 or a roughly equivalent course, or permission of instructor. Students should know what a proof is and how to produce one. Some informal understanding of probability is helpful, but students need not have taken a probability course.
Credit 3 units. A&S: NS A&S IQ: NSM

L24 Math 400 Undergraduate Independent Study
Approval of instructor required.
Credit variable, maximum 3 units.

L24 Math 403C Mathematical Logic I
A first course in mathematical logic, an introduction to both proof theory and model theory. The structure and properties of first-order logic are studied in detail, with attention to such notions as axiomatic theory, proof, model, completeness, compactness and decidability. Prerequisite: Phil 301G or equivalent, or a background in mathematics.
Same as L30 Phil 403
Credit 3 units. A&S: TH A&S IQ: HUM Art: HUM BU: HUM

L24 Math 404C Mathematical Logic II
Godel's Incompleteness Theorem: its proof, its consequences, its reverberations. Prerequisite: Phil 403 or a strong background in mathematics.
Same as L30 Phil 404
Credit 3 units. A&S: TH A&S IQ: HUM Art: HUM

L24 Math 406 Topics in Analysis: Special Bases in Analysis
The course considers the construction of specific orthonormal bases for the Hilbert spaces $L^2(R^n)$. We look at the Fourier series bases in $L^2([0,1])$, which are then used for the construction of two types of orthonormal bases in the more general setting of R^n: wavelets and Gabor bases. Some aspects of extensions to other Hilbert spaces are considered. In general, these bases are used to analyze "signals" or functions on R^n having either real or complex values, and they should be "efficient" in some sense. We look at the types of efficiency that are most useful in several types of application in sciences and engineering. Prerequisites: Math 233, 309, and 310, or permission of instructor. In particular, students are expected to understand derivatives and Riemann integration; topics related to the more general Lebesgue integral are discussed as needed.
Credit 3 units. A&S: NS A&S IQ: NSM

L24 Math 407 An Introduction to Differential Geometry
A study of properties of curves and surfaces in 3-dimensional Euclidean space. The course is essentially a modern recounting of a seminal paper of Gauss. Prerequisites: Math 233 and Math 309.
Credit 3 units. A&S: NS

L24 Math 408 Nonparametric Statistics
Statistical methods that make few or no assumptions about the data distribution. Permutation tests of different types; nonparametric confidence intervals and correlation coefficients; jackknife and bootstrap resampling; nonparametric regressions. If there is time, topics chosen from density estimation and kernel regression. Short computer programs will be written in a language like R or C. Prerequisites: CSE 131 or 200, Math 3200 and Math 493, or permission of instructor.
Credit 3 units. A&S: NS A&S IQ: NSM Art: NSM

L24 Math 410 Introduction to Fourier Series and Integrals
The basic theory of Fourier series and Fourier integrals including different types of convergence. Applications to certain differential equations. Prerequisites: Math 233 and Math 309.
Credit 3 units. A&S: NS A&S IQ: NSM

L24 Math 4111 Introduction to Analysis
The real number system and the least upper-bound property; metric spaces (completeness, compactness and connectedness); continuous functions (in R^n; on compact spaces; on connected spaces); $C(X)$ (pointwise and uniform convergence; Weierstrass approximation theorem); differentiation (mean value theorem; Taylor's theorem); the contraction mapping theorem; the inverse and implicit function theorems. Prerequisite: Math 310 or permission or instructor.
Credit 3 units. A&S: NS, QA A&S IQ: NSM

L24 Math 4121 Introduction to Lebesgue Integration
Riemann integration; measurable functions; measures; Lebesgue measure; the Lebesgue integral; integrable functions;

L^p spaces; modes of convergence; decomposition of measures; product measures. Prerequisite: Math 4111 or permission of the instructor.
Credit 3 units. A&S: NS A&S IQ: NSM Arch: NSM Art: NSM

L24 Math 415 Partial Differential Equations

Introduction to the theory of PDE's with applications to selected classical problems in physics and engineering. Linear and quasilinear first-order equations, derivation of some of the classical PDE's of physics, and standard solution techniques for boundary and initial value problems. Preliminary topics such as orthogonal functions, Fourier series and variational methods introduced as needed. Prerequisites: Math 217 and Math 309, or permission of instructor.
Credit 3 units. A&S: NS A&S IQ: NSM Art: NSM

L24 Math 416 Complex Variables

Analytic functions, elementary functions and their properties, line integrals, the Cauchy integral formula, power series, residues, poles, conformal mapping and applications. Prerequisites: Math 318, Math 308 or ESE 317, or permission of instructor.
Credit 3 units. A&S: NS A&S IQ: NSM Art: NSM

L24 Math 4171 Topology I

An introduction to the most important ideas of topology. Course includes necessary ideas from set theory, topological spaces, subspaces, products and quotients, compactness and connectedness. Some time is also devoted to the particular case of metric spaces (including topics such as separability, completeness, completions, the Baire Caregory Theorem, and equivalents of compactness in metric spaces). Prerequisite: Math 4111 or permission of instructor.
Credit 3 units. A&S: NS A&S IQ: NSM

L24 Math 418 Introduction to Topology and Modern Analysis II

Continuation of Math 417. May include some algebraic topology (depending on material covered in 417). Prerequisite: Math 417.
Credit 3 units. A&S: NS A&S IQ: NSM Art: NSM

L24 Math 4181 Topology II

A continuation of Math 4171 featuring more advanced topics in topology. The content may vary with each offering. Prerequisite: Math 4171, or permission of instructor.
Credit 3 units. A&S: NS A&S IQ: NSM

L24 Math 420 Experimental Design

A first course in the design and analysis of experiments, from the point of view of regression. Factorial, randomized block, split-plot, Latin square, and similar design. Prerequisite: CSE 131 or 200, Math 3200, or permission of instructor.
Credit 3 units. A&S: NS A&S IQ: NSM Art: NSM

L24 Math 429 Linear Algebra

Introduction to the linear algebra of finite-dimensional vector spaces. Includes systems of equations, matrices, determinants, inner product spaces, spectral theory. Prerequisite: Math 310 or permission of instructor. Math 309 is not an explicit prerequisite but students already should be familiar with such basic topics from matrix theory as matrix operations, linear systems, row reduction and Gaussian elimination. Material on these topics in early chapters of the text are covered very quickly.

Credit 3 units. A&S: NS, QA A&S IQ: NSM Art: NSM

L24 Math 430 Modern Algebra

Introduction to groups, rings and fields. Includes permutation groups, group and ring homomorphisms, field extensions, connections with linear algebra. Prerequisite: Math 429 or permission of the instructor.
Credit 3 units. A&S: NS A&S IQ: NSM Art: NSM

L24 Math 434 Survival Analysis

Life table analysis and testing, mortality and failure rates, Kaplan-Meier or product-limit estimators, hypothesis testing and estimation in the presence of random arrivals and departures, and the Cox proportional hazards model. Techniques of survival analysis are used in medical research, industrial planning and the insurance industry. Prerequisites: CSE 131 or 200, Math 309 and 3200, or permission of the instructor.
Credit 3 units. A&S: NS A&S IQ: NSM Art: NSM

L24 Math 4351 Number Theory and Cryptography

The course covers many of the basics of elementary number theory, providing a base from which to approach modern algebra, algebraic number theory and analytic number theory. It also introduces one of the most important real-world applications of mathematics, namely the use of number theory and algebraic geometry in public key cryptography. Topics from number theory involve divisibility (Euclidean algorithm, primes, Fundamental Theorem of Arithmetic), congruences (modular arithmetic, Chinese Remainder Theorem, primality testing and factorization). Topics from cryptography include RSA encryption, Diffie-Hellman key exchange and elliptic curve cryptography. Topics about algebraic numbers may be include if time permits. Prerequisites: Math 233, 309 and 310 (or permission of instructor).
Credit 3 units. A&S: NS A&S IQ: NSM

L24 Math 436 Algebraic Geometry

Introduction to affine and projective algebraic varieties; the Zariski topology; regular and rational mappings; simple and singular points; divisors and differential forms; genus; the Riemann-Roch theorem. Prerequisites: Math 318, Math 429 and Math 430, or permission of the instructor.
Credit 3 units. A&S: NS Art: NSM

L24 Math 439 Linear Statistical Models

Theory and practice of linear regression, analysis of variance (ANOVA) and their extensions, including testing, estimation, confidence interval procedures, modeling, regression diagnostics and plots, polynomial regression, colinearity and confounding, model selection, geometry of least squares, etc. The theory will be approached mainly from the frequentist perspective, and use of the computer (mostly R) to analyze data will be emphasized. Prerequisite: CSE 131 or 200, Math 3200 and a course in linear algebra (such as Math 309 or 429), or permission of instructor.
Credit 3 units. A&S: NS A&S IQ: NSM Art: NSM

L24 Math 4392 Advanced Linear Statistical Models

Review of basic linear models relevant for the course; generalized linear models including logistic and Poisson regression (heterogeneous variance structure, quasilikelihood); linear mixed-effects models (estimation of variance components, maximum likelihood estimation, restricted maximum likelihood, generalized estimating equations), generalized linear mixed-

effects models for discrete data, models for longitudinal data, optional multivariate models as time permits. The computer software R is used for examples and homework problems. Implementation in SAS is mentioned for several specialized models. Prerequisites: Math 439 and a course in linear algebra (such as Math 309 or Math 429), or consent of instructor.
Credit 3 units. A&S: NS A&S IQ: NSM Arch: NSM Art: NSM

L24 Math 449 Numerical Applied Mathematics
Computer arithmetic, error propagation, condition number and stability; mathematical modeling, approximation and convergence; roots of functions; calculus of finite differences; implicit and explicit methods for initial value and boundary value problems; numerical integration; numerical solution of linear systems, matrix equations and eigensystems; Fourier transforms; optimization. Various software packages may be introduced and used. Prerequisites: CSE 200 or CSE 131 (or other computer background with permission of the instructor); Math 217 and Math 309.
Credit 3 units. A&S: NS A&S IQ: NSM

L24 Math 450 Topics in Applied Mathematics
Topic may vary with each offering of the course. Prerequisites: CSE 131 (or 200) and Math 449, or permission of the instructor.
Credit 3 units. A&S: NS A&S IQ: NSM Art: NSM

L24 Math 456 Topics in Financial Mathematics
An introduction to the principles and methods of financial mathematics, with a focus on discrete-time stochastic models. Topics include no-arbitrage pricing of financial derivatives, risk-neutral probability measures, the Cox-Ross-Rubenstein and Black-Scholes-Merton options pricing models, and implied volatility. Prerequisites: Math 233 and Math 3200 or permission of instructor.
Credit 3 units. A&S: NS A&S IQ: NSM

L24 Math 459 Bayesian Statistics
Introduces the Bayesian approach to statistical inference for data analysis in a variety of applications. Topics include: comparison of Bayesian and frequentist methods, Bayesian model specification, choice of priors, computational methods such as rejection sampling, and stochastic simulation (Markov chain Monte Carlo), empirical Bayes method, hands-on Bayesian data analysis using appropriate software. Prerequisites: Math 493 and either Math 3200 or 494; or permission of the instructor. Some programming experience such as CSE 131 is also helpful (consult with the instructor).
Credit 3 units. A&S: NS A&S IQ: NSM

L24 Math 460 Multivariate Statistical Analysis
Review of basic random vectors and linear algebra relevant for the course; sample mean, variance and correlation as matrix operations and their geometric interpretation; multivariate normal distributions; sampling distributions and properties of sample mean and variance; Hotelling's T^2 and likelihood ratio tests; one-way MANOVA; two-way MANOVA; multivariate regression models; principal components analysis; factor analysis; discrimination and classification; clustering and grouping. The computer software R will be used for examples and homework problems. Implementation in SAS will be mentioned for several specialized analyses. Prerequisites: CSE 131 or 200, Math 493, Math 439, and a course in linear algebra (e.g., Math 309 or 429), or consent of instructor.

Credit 3 units. A&S: NS A&S IQ: NSM

L24 Math 461 Time Series Analysis
Time series data types; autocorrelation; stationarity and nonstationarity; autoregressive moving average models; model selection methods; bootstrap condence intervals; trend and seasonality; forecasting; nonlinear time series; filtering and smoothing; autoregressive conditional heteroscedasticity models; multivariate time series; vector autoregression; frequency domain; spectral density; state-space models; Kalman filter. Emphasis on real-world applications and data analysis using statistical software. Prerequisites: Math 493 and either Math 3200 or 494; or permission of the instructor. Some programming experience may also be helpful (consult with the instructor).
Credit 3 units. A&S IQ: NSM

L24 Math 469 Linear Algebra in Combinatorics
Many problems in combinatorics can be solved in surprising ways using linear algebra. The course will consider several types of problems to which linear algebra methods can be applied, reviewing some requisite ideas from linear algebra (and perhaps learning some new ones) along the way. Prerequisites: Math 310 and Math 429, or permission of instructor.
Credit 3 units. A&S: NS A&S IQ: NSM

L24 Math 470 Graph Theory
Graph theory entails aspects of counting theory, combinatorics, algebra, geometry and even some analysis. This course presents many of the most basic concepts and then develops several modern applications. Topics include fundamental results and uses of graphs, Euler's theorem, the adjacency matrix, eigenvalues and the Laplacian, isoperimetric problems, paths and flows, randomness in graphs, symmetric graphs, subgraphs, Harnack inequalities, Sobolev inequalities. Prerequisites Math 310 and Math 318 (or equivalent background with permission of the instructor).
Credit 3 units. A&S: NS A&S IQ: NSM

L24 Math 475 Statistical Computation
An introduction to programming in SAS (Statistical Analysis System) and applied statistics using SAS: contingency tables and Mantel-Haenszel tests; general linear models and matrix operations; simple, multilinear, and stepwise regressions; ANOVAs with nested and crossed interactions; ANOVAs and regressions with vector-valued data (MANOVAs). Topics chosen from discriminant analysis, principal components analysis, logistic regression, survival analysis, and generalized linear models. Prior acquaintance with SAS at the level introduced in Math 3200 is assumed. Prerequisites: CSE 131 or 200, Math 3200 and 493 (or 493 concurrently), or permission of instructor.
Credit 3 units. A&S: NS A&S IQ: NSM Art: NSM

L24 Math 481 Group Representations
Ideas and techniques in representation theory of finite groups and Lie groups.
Credit 3 units. A&S: NS

L24 Math 493 Probability
Mathematical theory and application of probability at the advanced undergraduate level; a calculus-based introduction to probability theory. Topics include the computational basics of probability theory, combinatorial methods, conditional probability

including Bayes' theorem, random variables and distributions, expectations and moments, the classical distributions, and the central limit theorem. Prerequisites: Math 318 or Math 308 and permission of the instructor.
Credit 3 units. A&S: NS A&S IQ: NSM Art: NSM

L24 Math 494 Mathematical Statistics
Theory of estimation, minimum variance and unbiased estimators, maximum likelihood theory, Bayesian estimation, prior and posterior distributions, confidence intervals for general estimators, standard estimators and distributions such as the Student-t and F-distribution from a more advanced viewpoint, hypothesis testing, the Neymann-Pearson Lemma (about best possible tests), linear models, and other topics as time permits. Prerequisites: CSE 131 or 200, Math 3200 and 493, or permission of the instructor.
Credit 3 units. A&S: NS A&S IQ: NSM Art: NSM

L24 Math 495 Stochastic Processes
Content varies with each offering of the course. Past offerings have included such topics as random walks, Markov chains, Gaussian processes, empirical processes, Markov jump processes and a short introduction to martingales, Brownian motion and stochastic integrals. Prerequisites: Math 318 and Math 493, or permission of instructor.
Credit 3 units. A&S: NS A&S IQ: NSM Art: NSM

L24 Math 496 Topics in Statistics
Topic varies with each offering.
Credit 3 units. A&S: NS Art: NSM

L24 Math 496A Topics in Algebra
Topic varies with each offering.
Credit 3 units. A&S: NS A&S IQ: NSM

L24 Math 497 Topics in Mathematics
Selected topics in undergraduate mathematics.
Credit 1 unit. A&S: NS Art: NSM

L24 Math 499 Study for Honors
Prerequisites: junior or senior standing, eligibility for honors work in mathematics and permission of the department's director of undergraduate studies.
Credit 3 units. Art: NSM