Mathematics and Statistics

This section presents the requirements for programs in:

- M.Sc. Mathematics with Concentration in Mathematics
- M.Sc. Mathematics and Statistics with Specialization in Bioinformatics
- M.Sc. Mathematics with Concentration in Statistics
- M.Sc. Mathematics and Statistics with Collaborative Specialization in Biostatistics
- Ph.D. Mathematics and Statistics

Program Requirements

Students must complete the requirements for the concentration in Mathematics or the concentration in Statistics. The M.Sc. in Mathematics and Statistics: Specialization in Bioinformatics is part of the M.Sc. in Mathematics and Statistics with Concentration in Mathematics. The M.Sc. in Mathematics and Statistics: Specialization in Biostatistics is part of the M.Sc. in Mathematics and Statistics with Concentration in Statistics.

- 2.0 credits in course work and 2.0 credits in a thesis, or
- 3.0 credits in course work and 1.0 credit in a research project, or
- 4.0 credits in course work.

M.Sc. Mathematics with Concentration in Mathematics (4.0 credits)

Requirements - Thesis Option (4.0 credits)

1. 2.0 credits in course work		2.0
2. 2.0 credits from:		2.0
MATH 5909 [2.0]	M.Sc. Thesis in Mathematics	
Total Credits		**4.0**

Requirements - Research Project option (4.0 credits)

1. 3.0 credits in course work		3.0
2. 1.0 credit from:		1.0
MATH 5910 [1.0]	M.Sc. Project in Mathematics	
Total Credits		**4.0**

Requirements - Course work option (4.0 credits)

1. 4.0 credits in courses		4.0
Total Credits		**4.0**

Notes:

1. Students must receive approval for course selection from their supervisor before registering in courses.
2. More than one half of the total required credits must be completed in the Concentration in Mathematics.
3. All master's students should normally participate in a seminar or research talks under the guidance of their supervisors.
4. A maximum of 1.0 credit taken outside of the School of Mathematics and Statistics at Carleton University or the Department of Mathematics and Statistics at the University of Ottawa may be allowed for credit, subject to the approval of the School.

M.Sc. Mathematics and Statistics with Specialization in Bioinformatics (4.5 credits)

Requirements:

1. 1.0 credit in:		1.0
BIOL 5515 [0.5]	Bioinformatics	
BIOL 5517 [0.5]	Bioinformatics Seminar	
2. 1.5 credits in coursework		1.5
3. 2.0 credits in:		2.0
MATH 5909 [2.0]	M.Sc. Thesis in Mathematics (on an approved bioinformatics topic)	
Total Credits		**4.5**

1. Students must receive approval for course selection from their supervisor before registering in courses.
2. All master's students should normally participate in a seminar or research talks under the guidance of their supervisors.

M.Sc. Mathematics with Concentration in Statistics (4.0 credits)

Requirements - Thesis Option (4.0 credits)

1. 2.0 credits in course work		2.0
2. 2.0 credits in:		2.0
STAT 5909 [2.0]	M.Sc. Thesis in Statistics	
Total Credits		**4.0**

Requirements - Research Project option (4.0 credits)

1. 3.0 credits in course work		3.0
2. 1.0 credit in:		1.0
STAT 5910 [1.0]	M.Sc. Project in Statistics	
Total Credits		**4.0**

Requirements - Course work option (4.0 credits)

1. 4.0 credits in courses		4.0
Total Credits		**4.0**

Notes:

1. Students must receive approval for course selection from their supervisor before registering in courses.
2. More than one half of the total required credits must be completed in the Concentration in Statistics.
3. All master's students should normally participate in a seminar or research talks under the guidance of their supervisors.
4. A maximum of 1.0 credit taken outside of the School of Mathematics and Statistics at Carleton University or the Department of Mathematics and Statistics at the University of Ottawa may be allowed for credit, subject to the approval of the School.

M.Sc. Mathematics and Statistics with Collaborative Specialization in Biostatistics (6.0 credits)

The M.Sc. in Mathematics and Statistics: Specialization in Biostatistics is part of the M.Sc. in Mathematics and Statistics with Concentration in Statistics and has two completion options.

Requirements - Thesis pathway (6.0 credits)		
1. 3.5 credits in course work		3.5
2. 0.5 credit in:		0.5
STAT 5902 [0.5]	Seminar in Biostatistics	
3. 2.0 credits in Thesis		2.0
Total Credits		**6.0**

Requirements - Coursework pathway (5.0 credits)		
1. 4.5 credits in courses		4.5
2. 0.5 credit in:		0.5
STAT 5902 [0.5]	Seminar in Biostatistics	
Total Credits		**5.0**

Unless prior approval by the Director of the collaborative program has been obtained, students in the M.Sc. Mathematics program should take EPIJ 5240, EPIJ 5241, EPIJ 6178, EPIJ 6278, STAT 5600 (MAT 5375) or STAT 5610 (MAT 5375), and STAT 5501 (MAT 5191) or STAT 5602 (MAT 5317). The remaining courses should be in Mathematics and Statistics at the graduate level.

Course Selection

Concentration in Mathematics

Mathematics	
All MATH courses are eligible for the Concentration in Mathematics.	
Statistics	
In addition, the following STAT courses may be used toward the Concentration in Mathematics:	
STAT 5501 [0.5]	Mathematical Statistics II
STAT 5504 [0.5]	Stochastic Processes and Time Series Analysis
STAT 5508 [0.5]	Topics in Stochastic Processes
STAT 5600 [0.5]	Mathematical Statistics I
STAT 5601 [0.5]	Stochastic Optimization
STAT 5604 [0.5]	Stochastic Analysis
STAT 5701 [0.5]	Stochastic Models
STAT 5704 [0.5]	Network Performance
STAT 5708 [0.5]	Probability Theory I
STAT 5709 [0.5]	Probability Theory II

Concentration in Statistics

Statistics	
All STAT courses are eligible for the Concentration in Statistics	

Undergraduate Courses

With the exception of students in the coursework option, all courses must be taken at the graduate level. Students in the coursework option may take up to 1.0 credit of undergraduate courses at the 4000 level from the following list:

MATH 4002 [0.5]	Fourier Analysis (Honours)
MATH 4105 [0.5]	Rings and Modules (Honours)
MATH 4107 [0.5]	Commutative Algebra (Honours)
MATH 4109 [0.5]	Fields and Coding Theory (Honours)
MATH 4207 [0.5]	Foundations of Geometry (Honours)
MATH 4208 [0.5]	Introduction to Differentiable Manifolds (Honours)
MATH 4700 [0.5]	Partial Differential Equations (Honours)
MATH 4703 [0.5]	Dynamical Systems (Honours)
MATH 4801 [0.5]	Topics in Combinatorics (Honours)
MATH 4802 [0.5]	Introduction to Mathematical Logic (Honours)
MATH 4803 [0.5]	Computable Functions (Honours)
MATH 4806 [0.5]	Numerical Linear Algebra (Honours)
MATH 4808 [0.5]	Graph Theory and Algorithms (Honours)
MATH 4811 [0.5]	Combinatorial Design Theory (Honours)
STAT 4501 [0.5]	Probability Theory (Honours) (may be used toward the Concentration in Mathematics)
STAT 4502 [0.5]	Survey Sampling (Honours)
STAT 4504 [0.5]	Statistical Design and Analysis of Experiments (Honours)
STAT 4506 [0.5]	Nonparametric Statistics (Honours)
STAT 4555 [0.5]	Monte Carlo Simulation (Honours) (may be used toward the Concentration in Mathematics)
STAT 4601 [0.5]	Data Mining I (Honours)
STAT 4603 [0.5]	Time Series and Forecasting (Honours)
STAT 4604 [0.5]	Statistical Computing (Honours)
All MATH courses are eligible for the Concentration in Mathematics.	
All STAT courses are eligible for the Concentration in Statistics.	

Ph.D. Mathematics and Statistics (3.0 credits)

Requirements:		
1. 3.0 credits in courses		3.0
2. 0.0 credits from:		0.0
MATH 6909 [0.0]	Ph.D. Thesis (including a final oral examination on the thesis subject)	
STAT 6909 [0.0]	Ph.D. Thesis (including a final oral examination on the thesis subject)	
3. All candidates must take comprehensive examinations. See note on Comprehensive Examinations below.		
Total Credits		**3.0**

Comprehensive Examinations

Students specializing in mathematics or probability undertake a comprehensive examination in the following areas:

- The candidate's general area of specialization at the Ph.D. level
- Examinations on two topics chosen from applied analysis, discrete applied mathematics, algebra, analysis, probability, topology, and statistics.

Students specializing in statistics must write an examination in the following areas:

- Mathematical statistics which includes multivariate analysis
- An examination in probability, and

- An examination in either (i) applied statistics or (ii) analysis.

In all cases, the examination must be completed successfully within twenty months of initial registration in the Ph.D. program in the case of full-time students, and within thirty-eight months of initial registration in the case of part-time students.

All Ph.D. candidates are also required to undertake a final oral examination on the subject of their thesis.

Regulations

See the General Regulations section of this Calendar.

Regularly Scheduled Break

For immigration purposes, the summer term (May to August) for the following programs is considered a regularly scheduled break approved by the University.

- M.Sc. Mathematics with Concentration in Mathematics (coursework and research essay pathways)
- M.Sc. Mathematics with Concentration in Statistics (coursework and research essay pathways)
- M.Sc. Mathematics and Statistics with Collaborative Specialization in Biostatistics (coursework pathway)

Students should resume full-time studies in September.

Note: a Regularly Scheduled Break as described for immigration purposes does not supersede the requirement for continuous registration in Thesis, Research Essay, or Independent Research Project as described in Section 8.2 of the Graduate General Regulations.

Admission

The normal requirement for admission to the master's program is an honours bachelor's degree in mathematics, statistics or the equivalent, with B+ or higher in the honours subject and B- or higher overall. Details are outlined in the General Regulations section of this Calendar.

Admission

The normal requirement for admission to the Ph.D. program is a master's degree in mathematics, or the equivalent, with at least B+ standing. Details are outlined in the General Regulations section of this Calendar.

Epidemiology - Joint (EPIJ) Courses

EPIJ 5240 [0.5 credit] (EPI 5240)
Epidemiology

EPIJ 5241 [0.5 credit] (EPI 5241)
Epidemiology II

EPIJ 5330 [0.5 credit] (EPI 5330)
Vital and Health Statistics

EPIJ 5340 [0.25 credit] (5340)
Epidemiological Methods
Major principles of study design and analysis: validity in epidemiologic studies; precision and statistics in epidemiology studies; confounding; additive and multiplicative interaction; stratified analysis; regression models; regression modeling; bias analysis; analytical strategy.
Includes: Experiential Learning Activity
Prerequisite(s): EPI 5240, (EPI 5242 or MAT 5375).

EPIJ 5344 [0.25 credit] (EPI 5344)
Survival Analysis in the Health Sciences
Types of survival data. Hazard function and its links to incidence rate/density. Nonparametric analysis including actuarial life tables, Kaplan-Meier method and log-rank test. Proportional hazards (Cox regression) modeling. Methods for time varying covariates and non-proportional hazards. SAS software for hands-on modeling.
Includes: Experiential Learning Activity
Prerequisite(s): EPI 5340.

EPIJ 5345 [0.25 credit] (EPI 5340)
Applied Logistic Regression
Foundation of model estimation: maximum likelihood; modeling dichotomous outcome (dependent) variables: logistic regression; logistic models with several independent variables; interpretation of model parameters; model-building strategies; assessing the fit of the model; regression diagnostics. Classes will include hands-on modeling examples using SAS statistical software.
Includes: Experiential Learning Activity
Prerequisite(s): EPI 5340.

EPIJ 5346 [0.25 credit] (EPI 5346)
Applied Longitudinal and Clustered Data Analysis
Introduction to longitudinal (repeated measures) and clustered data and overview of regression models for correlated data; linear mixed effects models: modelling the mean; modelling the covariance structure; generalized estimating equations and generalized linear mixed effects models; regression diagnostics; missing data and drop-out; case studies.
Includes: Experiential Learning Activity
Prerequisite(s): EPI 5340.

EPIJ 6178 [0.5 credit] (EPI 6178)
Clinical Trials

EPIJ 6278 [0.5 credit] (EPI 6278)
Advanced Clinical Trials

Mathematics (MATH) Courses

MATH 5001 [0.5 credit] (MAT 5144)
Commutative Algebra
Prime spectrum of a commutative ring (as a topological space); localization of rings and modules; tensor product of modules and algebras; Hilbert’s Nullstellensatz and consequences for finitely generated algebras; Krull dimension of a ring; integral dependence, going-up, going-down; Noether Normalization Lemma and dimension theory.

MATH 5002 [0.5 credit] (MAT 5149)
Algebraic Geometry
Brief overview of commutative algebra, Hilbert's Nullstellensatz, algebraic sets, and Zariski topology. Affine and projective varieties over algebraically closed fields. Regular functions and rational maps. Additional topics.

MATH 5003 [0.5 credit] (MAT 5122)
Banach Algebras
Commutative Banach algebras; the space of maximal ideals; representation of Banach algebras as function algebras and as operator algebras; the spectrum of an element. Special types of Banach algebras: for example, regular algebras with involution, applications.

MATH 5005 [0.5 credit] (MAT 5127)
Complex Analysis
Complex differentiation and integration, harmonic functions, maximum modulus principle, Runge's theorem, conformal mapping, entire and meromorphic functions, analytic continuation.

MATH 5007 [0.5 credit] (MAT 5125)
Real Analysis I (Measure Theory and Integration)
General measure and integral, Lebesgue measure and integration on R, Fubini's theorem, Lebesgue-Radon-Nikodym theorem, absolute continuity and differentiation, LP-spaces. Selected topics such as Daniell-Stone theory.
Also offered at the undergraduate level, with different requirements, as MATH 4007, for which additional credit is precluded.

MATH 5008 [0.5 credit] (MAT 5126)
Real Analysis II (Functional Analysis)
Banach and Hilbert spaces, bounded linear operators, dual spaces. Topics selected from: weak-topologies, Alaoglu's theorem, compact operators, differential calculus in Banach spaces, Riesz representation theorems.
Prerequisite(s): MATH 5007 (MAT 5125) or permission of the School.
Also offered at the undergraduate level, with different requirements, as MATH 4003, for which additional credit is precluded.

MATH 5009 [0.5 credit] (MAT 5121)
Introduction to Hilbert Space
Geometry of Hilbert Space, spectral theory of linear operators in Hilbert Space.

MATH 5102 [0.5 credit] (MAT 5148)
Group Representations and Applications
An introduction to group representations and character theory, with selected applications.

MATH 5103 [0.5 credit] (MAT 5146)
Rings and Modules
Generalizations of the Wedderburn-Artin theorem and applications, homological algebra.

MATH 5104 [0.5 credit] (MAT 5143)
Lie Algebras
Basic concepts: ideals, homomorphisms, nilpotent, solvable, semi-simple. Representations, universal enveloping algebra. Semi-simple Lie algebras: structure theory, classification, and representation theory.
Prerequisite(s): MATH 5107 (MAT 5141) and MATH 5109 (MAT 5142) or permission of the School.

MATH 5106 [0.5 credit] (MAT 5145)
Group Theory
Fundamental principles as applied to abelian, nilpotent, solvable, free, and finite groups; representations.
Also offered at the undergraduate level, with different requirements, as MATH 4106, for which additional credit is precluded.

MATH 5107 [0.5 credit] (MAT 5141)
Algebra I: Rings and Modules
Noetherian and artinian modules and rings. Varieties, Hilbert Basis Theorem, radical ideals, Hilbert Nullstellensatz. Localization and tensor products of modules and algebras. Semisimple rings and modules, Schur's Lemma, Jacobson Density Theorem, Artin-Wedderburn Theorem. Short exact sequences. Free, projective, injective and flat modules.

MATH 5108 [0.5 credit] (MAT 5147)
Homological Algebra and Category Theory
Axioms of set theory, categories, functors, natural transformations; free, projective, injective and flat modules; tensor products and homology functors, derived functors; dimension theory.
Also offered at the undergraduate level, with different requirements, as MATH 4108, for which additional credit is precluded.

MATH 5109 [0.5 credit] (MAT 5142)
Algebra II: Groups and Galois Theory
Group actions, class equation, Sylow theorems, central, composition and derived series, Jordan-Holder theorem, field extensions and minimal polynomials, algebraic closure, separable extensions, integrality, Galois groups, fundamental theorem of Galois theory, finite fields, cyclotomic field extensions, fundamental theorem of algebra, transcendental extensions.

MATH 5201 [0.5 credit] (MAT 5150)
Topics in Geometry
Various axiom systems of geometry. Detailed examinations of at least one modern approach to foundations, with emphasis upon the connections with group theory.

MATH 5202 [0.5 credit] (MAT 5168)
Homology Theory
The Eilenberg-Steenrod axioms and their consequences, singular homology theory, applications to topology and algebra.
Prerequisite(s): MATH 5205 (MAT 5151) or permission of the School.

MATH 5205 [0.5 credit] (MAT 5151)
Topology I
Topological spaces, product and identification topologies, countability and separation axioms, compactness, connectedness, homotopy, fundamental group, net and filter convergence.
Also offered at the undergraduate level, with different requirements, as MATH 4205, for which additional credit is precluded.

MATH 5206 [0.5 credit] (MAT 5152)
Topology II
Covering spaces, homology via the Eilenberg-Steenrod Axioms, applications, construction of a homology functor.
Prerequisite(s): MATH 5205 (MAT 5151) or permission of the School.
Also offered at the undergraduate level, with different requirements, as MATH 4206, for which additional credit is precluded.

MATH 5207 [0.5 credit] (MAT 5169)
Foundations of Geometry
A study of at least one modern axiom system of Euclidean and non-Euclidean geometry, embedding of hyperbolic and Euclidean geometries in the projective plane, groups of motions, models of non-Euclidean geometry.

MATH 5208 [0.5 credit] (MAT 5155)
Differentiable Manifolds
A study of differentiable manifolds from the point of view of either differential topology or differential geometry. Topics such as smooth mappings, transversality, intersection theory, vector fields on manifolds, Gaussian curvature, Riemannian manifolds, differential forms, tensors, and connections are included.

MATH 5300 [0.5 credit] (MAT 5160)
Mathematical Cryptography
Analysis of cryptographic methods used in authentication and data protection, with particular attention to the underlying mathematics, e.g. Algebraic Geometry, Number Theory, and Finite Fields. Advanced topics on Public-Key Cryptography: RSA and integer factorization, Diffie-Hellman, discrete logarithms, elliptic curves. Topics in current research.

MATH 5301 [0.5 credit] (MAT 5161)
Mathematical Logic
A basic graduate course in mathematical logic. Propositional and predicate logic, proof theory, Gentzen's Cut-Elimination, completeness, compactness, Henkin models, model theory, arithmetic and undecidability. Special topics (time permitting) depending on interests of instructor and audience.

MATH 5305 [0.5 credit] (MAT 5163)
Analytic Number Theory
Dirichlet series, characters, Zeta-functions, prime number theorem, Dirichlet's theorem on primes in arithmetic progressions, binary quadratic forms.

MATH 5306 [0.5 credit] (MAT 5164)
Algebraic Number Theory
Algebraic number fields, bases, algebraic integers, integral bases, arithmetic in algebraic number fields, ideal theory, class number.
Also offered at the undergraduate level, with different requirements, as MATH 4306, for which additional credit is precluded.

MATH 5403 [0.5 credit] (MAT 5187)
Topics in Applied Mathematics

MATH 5405 [0.5 credit] (MAT 5131)
Ordinary Differential Equations
Linear systems, fundamental solution. Nonlinear systems, existence and uniqueness, flow. Equilibria, periodic solutions, stability. Invariant manifolds and hyperbolic theory. One or two specialized topics taken from, but not limited to: perturbation and asymptotic methods, normal forms and bifurcations, global dynamics.

MATH 5406 [0.5 credit] (MAT 5133)
Partial Differential Equations
First-order equations, characteristics method, classification of second-order equations, separation of variables, Green's functions. Lp and Sobolev spaces, distributions, variational formulation and weak solutions, Lax-Milgram theorem, Galerkin approximation. Parabolic PDEs.
Wave equations, hyperbolic systems, nonlinear PDEs, reactiondiffusion equations, infinite-dimensional dynamical systems, regularity.

MATH 5407 [0.5 credit] (MAT 5134)
Topics in Partial Differential Equations
Theory of distributions, initial-value problems based on two-dimensional wave equations, Laplace transform, Fourier integral transform, diffusion problems, Helmholtz equation with application to boundary and initial-value problems in cylindrical and spherical coordinates.
Prerequisite(s): MATH 5406 or permission of the School.
Also offered at the undergraduate level, with different requirements, as MATH 4701, for which additional credit is precluded.

MATH 5408 [0.5 credit] (MAT 5185)
Asymptotic Methods of Applied Mathematics
Asymptotic series: properties, matching, application to differential equations. Asymptotic expansion of integrals: elementary methods, methods of Laplace, Stationary Phase and Steepest Descent, Watson's Lemma, Riemann-Lebesgue Lemma. Perturbation methods: regular and singular perturbation for differential equations, multiple scale analysis, boundary layer theory, WKB theory.

MATH 5605 [0.5 credit] (MAT 5165)
Theory of Automata
Algebraic structure of sequential machines, decomposition of machines; finite automata, formal languages; complexity.
Also offered at the undergraduate level, with different requirements, as MATH 4805/COMP 4805, for which additional credit is precluded.

MATH 5607 [0.5 credit] (MAT 5324)
Game Theory
Two-person zero-sum games; infinite games; multi-stage games; differential games; utility theory; two-person general-sum games; bargaining problem; n-person games; games with a continuum of players.
Also offered at the undergraduate level, with different requirements, as MATH 4807, for which additional credit is precluded.

MATH 5609 [0.5 credit] (MAT 5301)
Topics in Combinatorial Mathematics
Courses in special topics related to Combinatorial Mathematics, not covered by other graduate courses.

MATH 5801 [0.5 credit] (MAT 5303)
Linear Optimization
Linear programming problems; simplex method, upper bounded variables, free variables; duality; postoptimality analysis; linear programs having special structures; integer programming problems; unimodularity; knapsack problem.

MATH 5803 [0.5 credit] (MAT 5304)
Nonlinear Optimization
Methods for unconstrained and constrained optimization problems; Kuhn-Tucker conditions; penalty functions; duality; quadratic programming; geometric programming; separable programming; integer nonlinear programming; pseudo-Boolean programming; dynamic programming.

MATH 5804 [0.5 credit] (MAT 5307)
Topics in Operations Research

MATH 5805 [0.5 credit] (MAT 5308)
Topics in Algorithm Design

MATH 5806 [0.5 credit] (MAT 5180)
Numerical Analysis
Error analysis for fixed and floating point arithmetic; systems of linear equations; eigen-value problems; sparse matrices; interpolation and approximation, including Fourier approximation; numerical solution of ordinary and partial differential equations.

MATH 5807 [0.5 credit] (MAT 5167)
Formal Language and Syntax Analysis
Computability, unsolvable and NP-hard problems. Formal languages, classes of language automata. Principles of compiler design, syntax analysis, parsing (top-down, bottom-up), ambiguity, operator precedence, automatic construction of efficient parsers, LR, LR(O), LR(k), SLR, LL(k). Syntax directed translation.
Also listed as COMP 5807.
Prerequisite(s): MATH 5605.

MATH 5808 [0.5 credit] (MAT 5305)
Combinatorial Optimization I
Network flow theory and related material. Topics will include shortest paths, minimum spanning trees, maximum flows, minimum cost flows. Optimal matching in bipartite graphs.

MATH 5809 [0.5 credit] (MAT 5306)
Combinatorial Optimization II
Topics include optimal matching in non-bipartite graphs, Euler tours, and the Chinese Postman problem.
Other extensions of network flows: dynamic flows, multicommodity flows, and flows with gains, bottleneck problems. Matroid optimization. Enumerative and heuristic algorithms for the Traveling Salesman and other problems.
Prerequisite(s): MATH 5808 or permission of the school.

MATH 5818 [0.5 credit] (MAT 5105)
Discrete Applied Mathematics I: Graph Theory
Paths and cycles, trees, connectivity, Euler tours and Hamilton cycles, edge colouring, independent sets and cliques, vertex colouring, planar graphs, directed graphs. Selected topics from one or more of the following areas: algebraic graph theory, topological graph theory, random graphs.

MATH 5819 [0.5 credit] (MAT 5107)
Discrete Applied Mathematics II: Combinatorial Enumeration
Ordinary and exponential generating functions, product formulas, permutations, rooted trees, cycle index, WZ method. Lagrange inversions, singularity analysis of generating functions and asymptotics. Selected topics from one or more of the following areas: random graphs, random combinatorial structures, hypergeometric functions.

MATH 5821 [0.5 credit] (MAT 5341)
Quantum Computing
Space of quantum bits; entanglement. Observables in quantum mechanics. Density matrix and Schmidt decomposition. Quantum cryptography. Classical and quantum logic gates. Quantum Fourier transform. Shor's quantum algorithm for factorization of integers.
Precludes additional credit for COMP 4114.
Also offered at the undergraduate level, with different requirements, as MATH 4821, for which additional credit is precluded.

MATH 5822 [0.5 credit] (MAT 5343)
Mathematical Aspects of Wavelets and Digital Signal Processing
Lossless compression methods. Discrete Fourier transform and Fourier-based compression methods. JPEG and MPEG. Wavelet analysis. Digital filters and discrete wavelet transform. Daubechies wavelets. Wavelet compression.
Also offered at the undergraduate level, with different requirements, as MATH 4822, for which additional credit is precluded.

MATH 5900 [0.5 credit] (MAT 5990)
Seminar

MATH 5901 [0.5 credit] (MAT 5991)
Directed Studies

MATH 5906 [0.5 credit] (MAT 5996)
Research Internship
This course affords students the opportunity to undertake research in mathematics as a cooperative project with governmental or industrial sponsors. The grade will be based upon the mathematical content and upon oral and written presentation of results.
Includes: Experiential Learning Activity
Prerequisite(s): permission of the graduate director.

MATH 5909 [2.0 credits] (MAT 7999)
M.Sc. Thesis in Mathematics
Includes: Experiential Learning Activity

MATH 5910 [1.0 credit] (MAT 6997)
M.Sc. Project in Mathematics
Project in mathematics supervised by a professor approved by the graduate director resulting in a major report (approximately 30-40 pages), together with a short presentation on the report. Graded by the supervisor and another professor appointed by the graduate director.
Includes: Experiential Learning Activity
Precludes additional credit for MATH 5909.

MATH 5993 [0.0 credit] (MAT 5993)
Research Participation
Includes: Experiential Learning Activity

MATH 6002 [0.5 credit] (MAT 5309)
Harmonic Analysis on Groups
Transformation groups; Haar measure; unitary representations of locally compact groups; completeness and compact groups; character theory; decomposition.

MATH 6008 [0.5 credit] (MAT 5326)
Topics in Analysis

MATH 6101 [0.5 credit] (MAT 5327)
Topics in Algebra

MATH 6104 [0.5 credit] (MAT 5158)
Lie Groups
Matrix groups: one-parameter groups, exponential map, Campbell-Hausdorff formula, Lie algebra of a matrix group, integration on matrix groups. Abstract Lie groups.
Prerequisite(s): MATH 5007 and PADM 5107 or permission of the School.

MATH 6201 [0.5 credit] (MAT 5312)
Topics in Topology

MATH 6507 [0.5 credit] (MAT 5319)
Topics in Probability

MATH 6806 [0.5 credit] (MAT 5361)
Topics in Mathematical Logic

MATH 6807 [0.5 credit] (MAT 5162)
Mathematical Foundations of Computer Science
Foundations of functional languages, lambda calculi (typed, polymorphically typed, untyped), Curry-Howard Isomorphism, proofs-as-programs, normalization and rewriting theory, operational semantics, type assignment, introduction to denotational semantics of programs, fixed-point programming.

MATH 6900 [0.5 credit] (MAT 6990)
Seminar

MATH 6901 [0.5 credit] (MAT 6991)
Directed Studies

MATH 6909 [0.0 credit] (MAT 9999)
Ph.D. Thesis
Includes: Experiential Learning Activity

Statistics (STAT) Courses

STAT 5500 [0.5 credit] (MAT 5177)
Multivariate Normal Theory
Multivariate normal distribution properties, characterization, estimation of means, and covariance matrix. Regression approach to distribution theory of statistics; multivariate tests; correlations; classification of observations; Wilks' criteria.

STAT 5501 [0.5 credit] (MAT 5191)
Mathematical Statistics II
Confidence intervals and pivotals; Bayesian intervals; optimal tests and Neyman-Pearson theory; likelihood ratio and score tests; significance tests; goodness-of-fit-tests; large sample theory and applications to maximum likelihood and robust estimation.
Prerequisite(s): STAT 5600 or permission of the School.
Also offered at the undergraduate level, with different requirements, as STAT 4507, for which additional credit is precluded.

STAT 5502 [0.5 credit] (MAT 5192)
Sampling Theory and Methods
Unequal probability sampling with and without replacement; unified theory for standard errors; prediction approach; ratio and regression estimation; stratification and optimal designs; multistage cluster sampling; double sampling; domains of study; post-stratification; nonresponse; measurement errors; related topics.

STAT 5503 [0.5 credit] (MAT 5193)
Linear Models
Theory of non full rank linear models; estimable functions, best linear unbiased estimators, hypotheses testing, confidence regions; multi-way classifications; analysis of covariance; variance component models; maximum likelihood estimation, Minque, Anova methods; miscellaneous topics.
Prerequisite(s): STAT 5600 or permission of the School.

STAT 5504 [0.5 credit] (MAT 5194)
Stochastic Processes and Time Series Analysis
Stationary stochastic processes, inference for stochastic processes, applications to time series and spatial series analysis.

STAT 5505 [0.5 credit] (MAT 5195)
Design of Experiments
Overview of linear model theory; orthogonality; randomized block and split plot designs; latin square designs; randomization theory; incomplete block designs; factorial experiments: confounding and fractional replication; response surface methodology. Miscellaneous topics.
Prerequisite(s): STAT 5600 or permission of the School.

STAT 5506 [0.5 credit] (MAT 5175)
Robust Statistical Inference
Tests for location, scale, and regression parameters; derivation of rank tests; distribution theory of linear rank statistics and their efficiency. Robust estimation of location, scale and regression parameters; Huber's M-estimators, Rank-methods, L-estimators. Influence function. Adaptive procedures.
Prerequisite(s): STAT 5600 or permission of the School.

STAT 5507 [0.5 credit] (MAT 5176)
Advanced Statistical Inference
Pure significance test; uniformly most powerful unbiased and invariant tests; asymptotic comparison of tests; confidence intervals; large-sample theory of likelihood ratio and chi-square tests; likelihood inference; Bayesian inference; fiducial and structural methods; resampling methods.
Prerequisite(s): STAT 5501 or permission of the School.

STAT 5508 [0.5 credit] (MAT 5172)
Topics in Stochastic Processes
Course contents will vary, but will include topics drawn from Markov processes. Brownian motion, stochastic differential equations, martingales, Markov random fields, random measures, and infinite particle systems, advanced topics in modeling, population models.

STAT 5509 [0.5 credit] (MAT 5196)
Multivariate Analysis
Multivariate methods of data analysis, including principal components, cluster analysis, factor analysis, canonical correlation, MANOVA, profile analysis, discriminant analysis, path analysis.
Prerequisite(s): STAT 5600 or permission of the School.

STAT 5516 [0.5 credit] (MAT 5197)
Nonparametric Statistics
Order statistics; projections; U-statistics; L-estimators; rank, sign, and permutation test statistics; nonparametric tests of goodness-of-fit, homogeneity, symmetry, and independence; nonparametric density estimation; nonparametric regression analysis: kernel estimators, orthogonal series estimators, smoothing splines; high-dimensional inference problems and false discovery.
Prerequisite(s): STAT 5600 or permission of the School.
Also offered at the undergraduate level, with different requirements, as STAT 4506, for which additional credit is precluded.
Lectures three hours a week.

STAT 5600 [0.5 credit] (MAT 5190)
Mathematical Statistics I
Statistical decision theory; likelihood functions; sufficiency; factorization theorem; exponential families; UMVU estimators; Fisher's information; Cramer-Rao lower bound; maximum likelihood, moment estimation; invariant and robust point estimation; asymptotic properties; Bayesian point estimation.
Also offered at the undergraduate level, with different requirements, as STAT 4500, for which additional credit is precluded.

STAT 5601 [0.5 credit] (MAT 5197)
Stochastic Optimization
Topics chosen from stochastic dynamic programming, Markov decision processes, search theory, optimal stopping.

STAT 5602 [0.5 credit] (MAT 5317)
Analysis of Categorical Data
Analysis of one-way and two-way tables of nominal data; multi-dimensional contingency tables, log-linear models; tests of symmetry, marginal homogeneity in square tables; incomplete tables; tables with ordered categories; fixed margins, logistic models with binary response; measures of association and agreement.
Prerequisite(s): STAT 5600 and STAT 5501, or permission of the School.

STAT 5603 [0.5 credit] (MAT 5318)
Reliability and Survival Analysis
Types of censored data; nonparametric estimation of survival function; graphical procedures for model identification; parametric models and maximum likelihood estimation; exponential and Weibull regression models; nonparametric hazard function models and associate statistical inference; rank tests with censored data applications.
Prerequisite(s): STAT 5600 and STAT 5501 or permission of the School.

STAT 5604 [0.5 credit] (MAT 5173)
Stochastic Analysis
Brownian motion, continuous martingales, and stochastic integration.
Prerequisite(s): STAT 5708 or permission of the School.

STAT 5610 [0.5 credit] (MAT 5375)
Introduction to Mathematical Statistics
Limit theorems. Sampling distributions. Parametric estimation. Concepts of sufficiency and efficiency. Neyman-Pearson paradigm, likelihood ratio tests. Parametric and non-parametric methods for two- sample comparisons. Notions of experimental design, categorical data analysis, the general linear model, decision theory and Bayesian inference.
Precludes additional credit for STAT 5600.
Also offered at the undergraduate level, with different requirements, as STAT 4500, for which additional credit is precluded.

STAT 5701 [0.5 credit] (MAT 5198)
Stochastic Models
Markov systems, stochastic networks, queuing networks, spatial processes, approximation methods in stochastic processes and queuing theory. Applications to the modeling and analysis of computer-communications systems and other distributed networks.
Also offered at the undergraduate level, with different requirements, as STAT 4508, for which additional credit is precluded.

STAT 5702 [0.5 credit] (MAT 5182)
Modern Applied and Computational Statistics
Resampling and computer intensive methods: bootstrap, jackknife with applications to bias estimation, variance estimation, confidence intervals, and regression analysis. Smoothing methods in curve estimation; statistical classification and pattern recognition: error counting methods, optimal classifiers, bootstrap estimates of the bias of the misclassification error.

STAT 5703 [0.5 credit] (MAT 5181)
Data Mining
Visualization and knowledge discovery in massive datasets; unsupervised learning: clustering algorithms; dimension reduction; supervised learning: pattern recognition, smoothing techniques, classification. Computer software will be used.
Includes: Experiential Learning Activity
Precludes additional credit for DATA 5001.

STAT 5704 [0.5 credit] (MAT 5174)
Network Performance
Advanced techniques in performance evaluation of large complex networks. Topics may include classical queueing theory and simulation analysis; models of packet networks; loss and delay systems; blocking probabilities.

STAT 5705 [0.5 credit] (MAT 5373)
Statistical Machine Learning
Discriminant analysis, principal component analysis, support vector machines; reproducing kernel Hilbert spaces and kernel methods; neural networks; VC Theory, PAC learning. Additional topics may include: Bayesian modelling, manifold learning, boosting.
Includes: Experiential Learning Activity

STAT 5708 [0.5 credit] (MAT 5170)
Probability Theory I
Probability spaces, random variables, expected values as integrals, joint distributions, independence and product measures, cumulative distribution functions and extensions of probability measures, Borel-Cantelli lemmas, convergence concepts, independent identically distributed sequences of random variables.

STAT 5709 [0.5 credit] (MAT 5171)
Probability Theory II
Laws of large numbers, characteristic functions, central limit theorem, conditional probabilities and expectations, basic properties and convergence theorems for martingales, introduction to Brownian motion.
Prerequisite(s): STAT 5708 (MAT 5170) or permission of the School.

STAT 5713 [0.5 credit]
Advanced Data Mining
Topics from recent literature on mining complex data structures and data such as: tree/graph, sequence, web/test, stream, spatiotemporal, high-dimensional, multivariate time series, mixed-mode; clustering (EM, topic modeling, fuzzy), SVM; multi-label learning; deep learning; combining learners, network analysis/link prediction/ graphical models (Bayesian, Markov networks); anomaly detection.

STAT 5900 [0.5 credit] (MAT 5990)
Seminar

STAT 5901 [0.5 credit] (MAT 6991)
Directed Studies

STAT 5902 [0.5 credit] (MAT 5992)
Seminar in Biostatistics
Students work in teams on the analysis of experimental data or experimental plans. The participation of experimenters in these teams is encouraged. Student teams present their results in the seminar, and prepare a brief written report on their work.

STAT 5904 [0.5 credit] (MAT 5993)
Statistical Internship
This project-oriented course allows students to undertake statistical research and data analysis projects as a cooperative project with governmental or industrial sponsors. Practical data analysis and consulting skills will be emphasized. The grade will be based upon oral and written presentation of results.
Includes: Experiential Learning Activity
Prerequisite(s): permission of the graduate director.

STAT 5909 [2.0 credits]
M.Sc. Thesis in Statistics

STAT 5910 [1.0 credit]
M.Sc. Project in Statistics
Project in statistics supervised by a professor approved by the graduate director resulting in a major report (approximately 30-40 pages), together with a short presentation on the report. Graded by the supervisor and another professor appointed by the graduate director.
Includes: Experiential Learning Activity

STAT 6508 [0.5 credit] (MAT 5314)
Topics in Probability and Statistics

STAT 6900 [0.5 credit] (MAT 6990)
Seminar

STAT 6901 [0.5 credit] (MAT 6991)
Directed Studies

STAT 6909 [0.0 credit] (MAT 9999)
Ph.D. Thesis
Includes: Experiential Learning Activity