

# Mathematics

- **M.Sc. Mathematics (Applied Mathematics, Probability and Statistics, Pure Mathematics)**
- **M.Sc. Mathematics with Specialization in Bioinformatics**
- **M.Sc. Mathematics with Specialization in Biostatistics (Collaborative Program) (Specialization requirements listed under Biostatistics)**
- **Ph.D. Mathematics (Applied Mathematics, Probability and Statistics, Pure Mathematics)**

## M.Sc. Mathematics

### About the Program

Students pursuing studies in pure mathematics, applied mathematics, probability and statistics at the graduate level leading to an M.Sc. or a Ph.D. do so in a joint program offered by the School of Mathematics and Statistics at Carleton University and the Department of Mathematics and Statistics at the University of Ottawa under the auspices of the Ottawa-Carleton Institute of Mathematics and Statistics. The Institute is responsible for supervising the programs, regulations, and student admissions, and for providing a framework for interaction between the two departments at the research level.

### Academic Regulations

See the General Regulations section of this Calendar.

### Admission Requirements

The normal requirement for admission to the master's program is an Honours bachelor's degree in mathematics, or the equivalent, with at least high honours standing.

Applicants holding a general (three-year) degree with at least high honours standing may be admitted to a qualifying-year program.

Subsequent admission to the regular master's program depends on performance during the qualifying-year program and will be decided no later than one year after admission to the qualifying-year program. Details are outlined in the General Regulations section of this Calendar.

### Program Requirements

The three options for the M.Sc. program are:

- 2.0 credits and a thesis, or
- 3.0 credits and a research project, or
- 4.0 credits

#### M.Sc. Mathematics - Thesis Option (4.0 credits)

1. 2.0 credits in course work	2.0
2. 2.0 credits in:	2.0
MATH 5909 [2.0] M.Sc. Thesis	
<b>Total Credits</b>	<b>4.0</b>

#### M.Sc. Mathematics - Research Project option (4.0 credits)

1. 3.0 credits in course work	3.0
2. 1.0 credit in:	1.0

MATH 5910 [1.0] Project in Mathematics and Statistics	
<b>Total Credits</b>	<b>4.0</b>

#### M.Sc. Mathematics - Course work option (4.0 credits)

1. 4.0 credits in courses	4.0
<b>Total Credits</b>	<b>4.0</b>

#### Notes:

1. Students should consult their supervisors regarding their course selection to ensure that not all courses taken are in the same field of mathematics; at least 1.0 credit should be in another field.
2. All master's students are encouraged to participate in a seminar or project under the guidance of their supervisors.
3. 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.
4. Students who plan to specialize in probability or statistics are strongly advised that during their master's program they include, where possible, STAT 5600 Mathematical Statistics I, STAT 5501 Mathematical Statistics II, STAT 4502 Survey Sampling (Honours), STAT 5505 Design of Experiments, and STAT 4501 Probability Theory (Honours), STAT 5701 Stochastic Models. In addition, a graduate course in another field, such as biology, biostatistics, economics, computer science, systems analysis, and stochastic modeling, is highly recommended.

#### M.Sc. Mathematics with Specialization in Bioinformatics (5.0 credits)

1. 1.0 credit in:	1.0
BIOL 5515 [0.5] Bioinformatics	
BIOL 5517 [0.5] Bioinformatics Seminar	
2. 1.0 credit in coursework	1.0
2. 2.0 credits in:	2.0
MATH 5909 [2.0] M.Sc. Thesis (on an approved bioinformatics topic)	
<b>Total Credits</b>	<b>4.0</b>

### Course Selection

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:

#### Mathematics and Statistics

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)
STAT 4502 [0.5]	Survey Sampling (Honours)
STAT 4504 [0.5]	Statistical Design and Analysis of Experiments (Honours)
STAT 4601 [0.5]	Data Mining I (Honours)
STAT 4603 [0.5]	Time Series and Forecasting (Honours)
STAT 4604 [0.5]	Statistical Computing (Honours)
STAT 4605 [0.5]	Statistical Methods in Biostatistics (Honours)
STAT 4606 [0.5]	Practices in Biostatistics (Honours)

## Ph.D. Mathematics

### About the Program

Students pursuing studies in pure mathematics, applied mathematics, probability and statistics at the graduate level leading to an M.Sc. or a Ph.D. do so in a joint program offered by the School of Mathematics and Statistics at Carleton University and the Department of Mathematics and Statistics at the University of Ottawa under the auspices of the Ottawa-Carleton Institute of Mathematics and Statistics. The Institute is responsible for supervising the programs, regulations, and student admissions, and for providing a framework for interaction between the two departments at the research level.

### Academic Regulations

See the General Regulations section of this Calendar.

### Admission Requirements

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.

### Program Requirements

#### Ph.D. Mathematics (10.0 credits)

- 3.0 credits** in courses, at least 1.0 credit of which must be in a field other than mathematics 3.0
- 7.0 credits** in: 7.0
 

MATH 6909 [7.0]	Ph.D. Thesis (including a final oral examination on the thesis subject)
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3. All candidates must take comprehensive examinations. See note on Comprehensive Examinations below.

4. Language requirement. Determined by the candidate's advisory committee and normally requires the ability to read mathematical literature in a language considered useful for his/her research or career, and other than the candidate's principal language of study

Total Credits 10.0

### 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.

### Mathematics (MATH) Courses

#### 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  $\mathbb{R}$ , Fubini's theorem, Lebesgue-Radon-Nikodym theorem, absolute continuity and differentiation, LP-spaces. Selected topics such as Daniell-Stone theory. Also offered, with different requirements, as MATH 4007 for which additional credit is precluded.

Prerequisite(s): MATH 3001 or permission of the School.

**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. Also offered, with different requirements, as MATH 4003 for which additional credit is precluded.

Prerequisite(s): MATH 4007 or MATH 5007 (MAT 5125) or permission of the School.

**MATH 5009 [0.5 credit] (MAT 5121)****Introduction to Hilbert Space**

Geometry of Hilbert Space, spectral theory of linear operators in Hilbert Space.

Prerequisite(s): MATH 3001 and MATH 4003.

**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, with different requirements, as MATH 4106, for which additional credit is precluded.

Prerequisite(s): MATH 3106 or permission of the School.

**MATH 5107 [0.5 credit] (MAT 5141)****Algebra I**

Groups, Sylow subgroups, finitely generated abelian groups. Rings, field of fractions, principal ideal domains, modules. Polynomial algebra, Euclidean algorithm, unique factorization.

Prerequisite(s): permission of the School.

**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, with different requirements, as MATH 4108 for which additional credit is precluded.

Prerequisite(s): MATH 3106 and MATH 3158 or permission of the School.

**MATH 5109 [0.5 credit] (MAT 5142)****Algebra II**

Field theory, algebraic and transcendental extensions, finite fields, Galois groups. Modules over principal ideal domains, decomposition of a linear transformation, Jordan normal form.

Prerequisite(s): MATH 5107 (MAT 5141) and permission of the School.

**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.

Prerequisite(s): permission of the School.

**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 4205 or MATH 5205 (MAT 5151).

**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, with different requirements, as MATH 4205 for which additional credit is precluded.

Prerequisite(s): MATH 3001 or permission of the School.

**MATH 5206 [0.5 credit] (MAT 5152)****Topology II**

Covering spaces, homology via the Eilenberg-Steenrod Axioms, applications, construction of a homology functor. Also offered, with different requirements, as MATH 4206 for which additional credit is precluded.

Prerequisite(s): MATH 3106, MATH 3158 and MATH 5205 (MAT 5151) or permission of the School.

**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.

Prerequisite(s): MATH 3106 (may be taken concurrently) or permission of the School.

**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.

Prerequisite(s): MATH 3001 or permission of the School.

**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.

Prerequisite(s): undergraduate honours algebra, including group theory and finite fields.

**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.

Prerequisite(s): Honours undergraduate algebra, analysis and topology or permission of the instructor.

**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.

Prerequisite(s): MATH 3057 or permission of the School.

**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, with different requirements, as MATH 4306 for which additional credit is precluded.

Prerequisite(s): MATH 3158 or permission of the School.

**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.

Prerequisite(s): MATH 3008 or permission of the School.

**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.  $L_p$  and Sobolev spaces, distributions, variational formulation and weak solutions, Lax-Milgram theorem, Galerkin approximation. Parabolic PDEs.

Wave equations, hyperbolic systems, nonlinear PDEs, reaction-diffusion equations, infinite-dimensional dynamical systems, regularity.

Prerequisite(s): MATH 3008 or permission of the School.

**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. Also offered, with different requirements, as MATH 4701 for which additional credit is precluded.

Prerequisite(s): MATH 5406 or permission of the School.

**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, WKBJ theory.

Prerequisite(s): MATH 3057 and at least one of MATH 3008 and MATH 3705, or permission of the School.

**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, with different requirements, as MATH 4805/COMP 4805 for which additional credit is precluded.

Prerequisite(s): MATH 2100 or permission of the School.

**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, with different requirements, as MATH 4807 for which additional credit is precluded.

Prerequisite(s): MATH 3001 or permission of the School.

**MATH 5609 [0.5 credit] (MAT 5301)****Topics in Combinatorial Mathematics**

Prerequisite(s): permission of the School.

**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.

Prerequisite(s): course in linear algebra and permission of the School.

**MATH 5802 [0.5 credit] (MAT 5325)****Introduction to Information and Systems Science**

Introduction to the process of applying computers in problem solving. Emphasis on the design and analysis of efficient computer algorithms for large, complex problems. Applications: data manipulation, databases, computer networks, queuing systems, optimization. Also listed as SYSC 5802, COMP 5802 and ISYS 5802.

**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. Prerequisite(s): permission of the School.

**MATH 5804 [0.0 credit] (MAT 5307)****Topics in Operations Research****MATH 5805 [0.05 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. Prerequisite(s): permission of the School.

**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 or MATH 4805 or COMP 3002, or permission of the School.

**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.

Prerequisite(s): permission of the School.

**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 "hard" problems.

Prerequisite(s): MATH 5808.

**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.

Prerequisite(s): MATH 3855 or permission of the School.

**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.

Prerequisite(s): MATH 3855 or permission of the School.

**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.

Prerequisite(s): MATH 1102, or permission of the School.

**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, with different requirements, as MATH 4822, for which additional credit is precluded.

Prerequisites: Linear algebra and Fourier series, or permission of the School.

Prerequisite(s): Linear algebra and Fourier series, or permission of the School.

**MATH 5900 [0.5 credit] (MAT 5990)****Seminar****MATH 5901 [0.5 credit] (MAT 5991)****Directed Studies**

**MATH 5903 [0.5 credit]****Project**

Intended for students registered in Information and Systems Science and M.C.S. programs. Students pursuing the non-thesis option will conduct a study, analysis, and/or design project. Results will be given in the form of a typewritten report and oral presentation.

**MATH 5906 [0.5 credit] (MAT 5993)****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.

Prerequisite(s): permission of the graduate director.

**MATH 5908 [1.5 credit] (MAT 5993)****M.Sc. Thesis in Information and Systems Science**

Also listed as COMP 5908, ISYS 5908, SYSC 5908.

**MATH 5909 [2.0 credits]****M.Sc. Thesis****MATH 5910 [1.0 credit] (MAT 6097)****Project in Mathematics and Statistics**

Project in mathematics and 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. The project will normally be completed in one term.

Precludes additional credit for MATH 5909.

Prerequisite(s): approval of the graduate director.

**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 6009 [0.5 credit] (MAT 5329)****Topics in Analysis****MATH 6101 [0.5 credit] (MAT 5327)****Topics in Algebra****MATH 6102 [0.5 credit] (MAT 5330)****Topics in Algebra****MATH 6103 [0.5 credit] (MAT 5331)****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 5313)****Topics in Probability & Stats****MATH 6508 [0.5 credit] (MAT 5314)****Topics in Probability & Stats****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.

Prerequisite(s): honours undergraduate algebra and either topology or analysis, permission of the instructor or some acquaintance with logic.

**MATH 6900 [0.5 credit] (MAT 6990)****Seminar****MATH 6901 [0.5 credit] (MAT 6991)****Directed Studies****MATH 6909 [7.0 credits] (MAT 6991)****Ph.D. Thesis****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.

Prerequisite(s): STAT 3559.

**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. Also offered, with different requirements, as STAT 4507 for which additional credit is precluded.

Prerequisite(s): STAT 4500 or STAT 5600 or permission of the School.

**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.

Prerequisite(s): STAT 4502 or permission of the School.

**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 4500 or 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.

Prerequisite(s): STAT 4501 or permission of the School.

**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 3553 and STAT 4504 or STAT 4500 or 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 4500 or 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 4507 or 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, etc.

Prerequisite(s): STAT 3506 or STAT 4501, or permission of the School.

**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 4500 or STAT 5600 or permission of the School.

**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, with different requirements, as MATH 4500 for which additional credit is precluded.

Prerequisite(s): STAT 3559 or permission of the School.

**STAT 5601 [0.5 credit] (MAT 5197)****Stochastic Optimization**

Topics chosen from stochastic dynamic programming, Markov decision processes, search theory, optimal stopping.

Prerequisite(s): STAT 3506 or permission of the School.

**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 4500 or STAT 5600, STAT 4507 or 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 4500 or STAT 5600, STAT 4507 or 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 4501 or 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.

Prerequisite(s): STAT 3553 and STAT 2559 or permission of the School.

**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, with different requirements, as STAT 4508 for which additional credit is precluded.

Prerequisite(s): STAT 3506 or permission of the School.

**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.

Prerequisite(s): permission of the instructor.

**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.

Prerequisite(s): permission of the instructor.

**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.

Prerequisite(s): some familiarity with probability and stochastic processes and queueing, or permission of the instructor.

**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.

Prerequisite(s): MATH 3001, and STAT 3558 is strongly recommended, or permission of the School.

**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 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]****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.

Prerequisite(s): permission of the graduate director.

**Summer session:** some of the courses listed in this Calendar are offered during the summer. Hours and scheduling for summer session courses will differ significantly from those reported in the fall/winter Calendar. To determine the scheduling and hours for summer session classes, consult the class schedule at [central.carleton.ca](http://central.carleton.ca)

Not all courses listed are offered in a given year. For an up-to-date statement of course offerings for the current session and to determine the term of offering, consult the class schedule at [central.carleton.ca](http://central.carleton.ca)