

Computer Science

This section presents the requirements for programs in:

- **M.C.S. Computer Science**
- **M.C.S. Computer Science with Collaborative Specialization in Cybersecurity**
- **M.C.S. Computer Science with Collaborative Specialization in Data Science**
- **Ph.D. Computer Science**

Program Requirements

M.C.S. Computer Science (5.0 credits)

Requirements - Thesis pathway (5.0 credits)

1. **2.5 credits in** course work. Course work must include a minimum of 1.5 credits of OCICS courses in three different research areas (see OCICS course listing by research areas). 2.5

2. **2.5 credits in:** 2.5

COMP 5905 [2.5]	M.C.S. Thesis (Each candidate submitting a thesis will be required to undertake an oral defence of the thesis.)
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Total Credits 5.0

Requirements - Non-Thesis pathway (5.0 credits)

1. **4.0 credits in** course work. Course work must include a minimum of 1.5 credits of OCICS courses in three different research areas (see OCICS course listing by research areas). 4.0

2. **1.0 credits in** Graduate project OR additional OCICS courses 1.0

COMP 5903 [1.0]	Graduate Project (M.C.S.)
OR	
1.0 credits of additional OCICS courses	

Total Credits 5.0

M.C.S. Computer Science with Collaborative Specialization in Cybersecurity (5.0 credits)

Requirements - Thesis pathway (5.0 credits)

1. **1.0 credit in:** 1.0

CYBR 5000 [1.0]	Science and Social Science of Cybersecurity
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2. **1.5 credits in** course work. Course work must include a minimum of 1.5 credits of OCICS courses in three different research areas (see OCICS course listing by research areas). 1.5

3. **2.5 credits in** graduate thesis (Each candidate submitting a thesis will be required to undertake an oral defence of the thesis). 2.5

COMP 5905 [2.5]	M.C.S. Thesis (in the area of the specialization)
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Total Credits 5.0

Requirements - Non-Thesis pathway (5.0 credits)

1. **1.0 credit in:** 1.0

CYBR 5000 [1.0]	Science and Social Science of Cybersecurity
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2. **3.0 credits in** course work. Course work must include a minimum of 1.5 credits of OCICS courses in three different research areas (see OCICS course listing by research areas). 3.0

3. **1.0 credit in** Graduate project OR additional OCICS courses. 1.0

COMP 5903 [1.0]	Graduate Project (M.C.S.) (in the area of the specialization)
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OR

1.0 credits of additional OCICS courses

Total Credits 5.0

M.C.S. Computer Science with Collaborative Specialization in Data Science (5.0 credits)

Requirements - Thesis pathway (5.0 credits)

1. **0.5 credit in:** 0.5

DATA 5000 [0.5]	Introduction to Data Science
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2. **2.0 credits in** course work. Course work must include a minimum of 1.5 credits of OCICS courses in at least three different research areas. See OCICS course listing by research areas. 2.0

3. **2.5 credits in:** 2.5

COMP 5905 [2.5]	M.C.S. Thesis (M.C.S. Thesis must be in an area of Data Science and requires approval from the Institute of Data Science. Each candidate submitting a thesis will be required to undertake an oral defence of the thesis.)
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Total Credits 5.0

Ph.D. Computer Science (1.5 credits)

Requirements:

1. **1.5 credits in** OCICS courses within the first 4 terms. 1.5

The admission committee and the student's advisory committee may impose additional program requirements according to the student's background and research topic.

2. Requirement of two seminars.

3. **0.0 credit in:** 0.0

COMP 6907 [0.0]	Doctoral Comprehensive (involving breadth and depth components, must be taken within the first 4 terms)
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4. **0.0 credit in:** 0.0

COMP 6908 [0.0]	Doctoral Proposal (defended at an oral examination within the first 6 terms)
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5. **0.0 credits in:**

COMP 6909 [0.0]	Ph.D. Thesis (defended at an oral examination)
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Total Credits 1.5

OCICS Graduate Courses

The Ottawa-Carleton Institute for Computer Science (OCICS) is a joint program consisting of the School of Electrical Engineering and Computer Science (EECS) at the University of Ottawa and the School of Computer Science (SCS) at Carleton University.

MCS students must complete a minimum of 1.5 credits of OCICS courses across at least three different research areas:

Software Engineering (E)
Theory of Computing (T)
Computer Applications (A)
Computer Systems (S)

Please note that courses with COMP (CSI) designation are offered by SCS, while courses with CSI (COMP) designation are offered by EECS.

For a list of courses in the various research areas, please refer to the OCICS List of Courses page. Please note that not all courses on the OCICS List of Courses page are offered in a given year. Please consult the Public Class Schedule for up-to-date course offerings for each academic term and refer to the OCICS Course Timetable for specific area requirements.

Admission

M.C.S.

M.C.S. with Collaborative Specialization in Data Science

M.C.S with Collaborative Specialization in Cybersecurity

See the General Regulations section of this Calendar for detailed admission requirements. Applicants should have an honours bachelor's degree in computer science or the equivalent. By equivalent is meant an honours degree in a program that includes at least twelve computer science half-credits, two of which must be at the 4000-level, and eight half-credits in mathematics, one of which must be at the 3000- or 4000-level.

Applicants who have a three-year non-honours bachelor's degree, or who otherwise lack the required undergraduate preparation, may be admitted to a qualifying-year program. Refer to the General Regulations section of this Calendar for regulations governing the qualifying year.

Accelerated Pathway

The accelerated pathway in the Master of Computer Science (M.C.S.) program is a flexible and individualized plan of graduate study. Students in their third year of the Bachelor of Computer Science (Hons.) or Bachelor of Cybersecurity (Hons.) programs at Carleton with demonstrated academic excellence and aptitude for research may qualify for this option.

Students in their third year of study in the B.C.S. (Hons.) or B.Cyber. (Hons.) programs should consult with both an SCS Undergraduate Advisor and the Graduate Director to determine if the accelerated pathway is appropriate for them and to confirm their course selection for their final year of undergraduate studies.

If approved for the M.C.S. Accelerated Pathway, students may take up to two 5000-level COMP courses (up to 1.0 credit) in their fourth year. If the student wishes to apply and is admitted to the M.C.S. program, the 5000-level COMP courses taken as part of the B.C.S. (Hons.) or B.Cyber. (Hons.) may receive advanced standing of up to 1.0 credit, provided the grades achieved are B+ or greater.

This can reduce the time required to complete the M.C.S. program.

Requirements for Eligibility to the Accelerated Pathway

1. Third year standing in the B.C.S. (Hons.) or B.Cyber. (Hons.) program with substantial completion of the required courses at the 3000-level and below.
2. Major CGPA of at least 10.0.

Requirements for Eligibility to the M.C.S. program after completing the Accelerated Pathway

1. 0.5 credit in COMP at the 5000-level with a grade of B+ or higher.
2. Minimum overall and Major CGPA of A-.

Admission

See the General Regulations section of this Calendar for detailed admission requirements.

1. **Admission with Master's degree:** the normal requirement for admission to the Ph.D. program is a thesis-based Master of Computer Science (M.C.S.) or the equivalent demonstrating research potential.
2. **Admission with Bachelor's degree:** exceptional applicants holding an Honours Bachelor of Computer Science with thesis or equivalent, with demonstrated research potential and with a minimum GPA of A- in Computer Science, may be directly admitted to the Ph.D. program. It is highly recommended that applicants considering this option contact potential supervisors before applying.
3. **Fast-track:** at the request of their supervisor, a student already in the M.C.S. with demonstrated research potential and who has completed at least 3 graduate courses with an A or A+ may be fast-tracked to the Ph.D. before they complete the first year of their M.C.S.

Co-operative Education

For information about how to apply for the Co-op program and how the Co-op program works, visit the Co-op website.

All graduate students participating in the Co-op program are governed by this Graduate Co-operative Education Policy.

Application Requirements

Graduate students are encouraged to apply to the Co-op Program during their first term of studies. Alternatively, students may delay their participation until later on, provided that they have mandatory credits remaining for degree completion.

Participation Requirements

Graduate students:

- must be registered as full-time before they begin their co-op job search and their co-op work term.
- will be registered in a Co-op Work Term course while at work. This course does not carry academic course credit, but is noted on academic transcripts.

- may register in a 0.5 credit during a work term, provided the course is offered during the evening or is offered asynchronously online.
- are not permitted to hold a Teaching Assistantship while on a co-op work term. Where eligible, Teaching Assistantships will be deferred to a later term.
- in receipt of internal or external scholarships should contact Graduate Studies to discuss the possible funding implications of being on a co-op work term
- must have mandatory courses left to complete following their final co-op work term. In cases where the graduate student has just a 0.5 credit left, they may request permission of the Co-op Office to complete this course during the work term.

Co-op Participation Agreement

All graduate students must adhere to the policies found within the Co-op Participation Agreement.

Communication with the Co-op Office

Graduate students must maintain regular contact with the Co-op Office during their job search and while on a work term. All email communication will be conducted via the student's Carleton email account.

Graduation with the Co-op Designation

In order to graduate with the Co-op Designation, graduate students must satisfy all requirements of the degree program in addition to the successful completion of two work terms. Students found in violation of the Co-op Participation Agreement may have the Co-op Designation withheld.

Employment

Although every effort is made to ensure a sufficient number of job postings for all Co-op students, no guarantee of employment can be made. The Co-op job search process is competitive, and success is dependent upon factors such as current market conditions, academic performance, skills, motivation, and level of commitment to the job search. It is the student's responsibility to apply for positions via the Co-op job board in addition to actively conducting a self-directed job search. Students who do not obtain a co-op work term are expected to continue with their academic studies. It should be noted that hiring priority for positions within the Federal Government of Canada is given to Canadian citizens.

Work Term Assessment and Evaluation

Work Term Evaluation

Employers are responsible for submitting to Carleton University final performance evaluations for their Co-op students at the end of their work terms.

Work Term Assessment

In order to successfully complete the co-op work term, graduate students must receive a Satisfactory (SAT) grade on their Co-op Work Term Report, which they must submit at the completion of each four-month work term.

Voluntary Withdrawal from the Co-op Option

Students who are currently on a co-op work term or who have already committed to a co-op work term either verbally or in writing may not leave the position and/or

withdraw from the co-op option until they have completed the requirements of the work term.

Involuntary or Required Withdrawal from the Co-op Option

Graduate students may be removed from the Co-op Program for any of the following reasons:

1. Failure to attend all interviews for positions to which the student has applied;
2. Declining more than one job offer during the job search;
3. Reneging on a co-op position that the student has accepted either verbally or in writing;
4. Continuing a job search after accepting a co-op position;
5. Dismissal from a work term by the co-op employer;
6. Leaving a work term without approval from the Co-op Management Team;
7. Receipt of an unsatisfactory work term evaluation;
8. Receiving a grade of UNS on the work term report;

International Students

International students must be legally eligible to work in Canada, as per requirements set out by Immigration, Refugees, and Citizenship Canada (IRCC).

Co-op Fees

All participating Co-op students are required to pay Co-op fees. For full details, please see the Co-op website.

Computer Science Co-operative Education Option

Students are encouraged to apply for admission to the Co-operative Education Program by the end of their first term of academic study.

To be eligible for admission to Co-op, students must:

1. be enrolled in the Master of Computer Science;
2. have achieved, by the end of their first term of academic study, a minimum grade of A- in at least two 5000-level COMP courses;
3. have achieved, by the start-date of the first work term, a minimum grade of A- in at least four 5000-level COMP courses;
4. be registered as a full-time student in each academic term prior to a work term;
5. be eligible to work in Canada (for off-campus work terms)

For more information, please refer to the Co-operative Education Policy.

Regulations

See the General Regulations section of this Calendar.

Regularly Scheduled Break

For immigration purposes, the summer term (May to August) for the Master of Computer Science program, including all specializations/concentrations within the program, is considered a regularly scheduled break

approved by Carleton University. 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.

Computer Science (COMP) Courses

Note:

- Course credit preclusions: certain Computer Science courses listed below may have been available as an undergraduate section. Students who have completed an undergraduate course at Carleton University with the same instructor and a similar title are not eligible to take the graduate section for credit. Please consult the department with questions.

COMP 5001 [0.5 credit] (CSI 5113)

Foundations of Programming Languages

Advanced study of programming paradigms from a practical perspective. Paradigms may include functional, imperative, concurrent, distributed, generative, aspect- and object-oriented, and logic programming. Emphasis on underlying principles. Topics may include: types, modules, inheritance, semantics, continuations, abstraction and reflection.

COMP 5002 [0.5 credit] (CSI 5128)

Swarm Intelligence

Collective computation, collective action, and principles of self-organization in social agent systems. Algorithms for combinatorial optimization problems, division of labour, task allocation, task switching, and task sequencing with applications in security, routing, wireless and ad hoc networks and distributed manufacturing.

COMP 5003 [0.5 credit] (CSI 5308)

Principles of Distributed Computing

Formal models of distributed environment; theoretical issues in the design of distributed algorithms; message and time complexity; problem solving in distributed settings. Problems discussed may include: coordination and control, information diffusion, leader election, consensus, distributed data operations, computing by mobile entities.

COMP 5004 [0.5 credit] (CSI 5134)

Fault Tolerance

Hardware and software techniques for fault tolerance. Topics include modeling and evaluation techniques, error detecting and correcting codes, module and system level fault detection mechanisms, design techniques for fault-tolerant and fail-safe systems, software fault tolerance through recovery blocks, N-version programming, algorithm-based fault tolerance, checkpointing.

COMP 5005 [0.5 credit] (CSI 5390)

Learning Systems for Random Environments

Computerized adaptive learning for random environments and its applications. Topics include a mathematical review, learning automata which are deterministic/stochastic, with fixed/variable structures, of continuous/discretized design, with ergodic/absorbing properties and of estimator families.

COMP 5007 [0.5 credit] (CSI 5149)

Graphical Models and Applications

Bayesian networks, factor graphs, Markov random fields, maximum a posteriori probability (MAP) and maximum likelihood (ML) principles, elimination algorithm, sum-product algorithm, decomposable and non-decomposable models, junction tree algorithm, completely observed models, iterative proportional fitting algorithm, expectation-maximization (EM) algorithm, iterative conditional modes algorithm.

COMP 5008 [0.5 credit] (CSI 5164)

Computational Geometry

Study of design and analysis of algorithms to solve geometric problems; emphasis on applications such as robotics, graphics, and pattern recognition. Topics include: visibility problems, hidden line and surface removal, path planning amidst obstacles, convex hulls, polygon triangulation, point location.

COMP 5100 [0.5 credit] (CSI 5180)

Topics in Artificial Intelligence

Areas in knowledge-based systems including recent approaches to machine learning and data mining, inference methods, knowledge-based and fuzzy systems, heuristic search, and natural language processing. Precludes additional credit for COMP 4106 (no longer offered).

COMP 5101 [0.5 credit] (CSI 5311)

Distributed Databases and Transaction Processing Systems

Principles in the design and implementation of distributed databases and distributed transaction processing systems. Topics include: distributed computing concepts, computing networks, distributed and multi-database system architectures and models, atomicity, synchronization and distributed concurrency control algorithms, data replication, recovery techniques, reliability in distributed databases.

COMP 5102 [0.5 credit] (CSI 5312)**Distributed Operating Systems**

An advanced course on the software infrastructure supporting large-scale cloud computing applications. Topics may include: distributed file systems, distributed databases, overlay networks, container orchestration, coordination services, security and privacy services, and large-scale AI pipelines.

Also offered at the undergraduate level, with different requirements, as COMP 4000, for which additional credit is precluded.

COMP 5103 [0.5 credit] (CSI 5148)**Wireless Ad Hoc Networking**

Self-organized, mobile, and hybrid ad hoc networks. Physical, medium access, networks, transport and application layers, and cross-layering issues. Power management. Security in ad hoc networks. Topology control and maintenance. Data communication protocols, routing and broadcasting. Location service for efficient routing.

COMP 5104 [0.5 credit] (CSI 5314)**Object-Oriented Software Development**

Issues in modeling and verifying quality and variability in object-oriented systems. Testable models in model-driven and test-driven approaches. System family engineering. Functional conformance: scenario modeling and verification, design by contract. Conformance to non functional requirements: goals, forces and tradeoffs, metrics.

COMP 5107 [0.5 credit] (CSI 5185)**Statistical and Syntactic Pattern Recognition**

Topics include a mathematical review, Bayes decision theory, maximum likelihood and Bayesian learning for parametric pattern recognition, non-parametric methods including nearest neighbor and linear discriminants. Syntactic recognition of strings, substrings, subsequences and tree structures. Applications include speech, shape and character recognition.

COMP 5108 [0.5 credit] (CSI 5126)**Algorithms in Bioinformatics**

Fundamental mathematical and algorithmic concepts underlying computational molecular biology; physical and genetic mapping, sequence analysis (including alignment and probabilistic models), genomic rearrangement, phylogenetic inference, computational proteomics and systemics modelling of the whole cell.

COMP 5110 [0.5 credit] (CSI 5136)**Computer Security and Usability**

This course focuses on designing and evaluating security and privacy software with particular attention to human factors and how interaction design impacts security. Topics include current approaches to usable security, methodologies for empirical analysis, and design principles for usable security and privacy.

COMP 5111 [0.5 credit] (CSI 5153)**Data Management for Business Intelligence**

Application of computational techniques to support business such as decision making, business understanding, data analysis, business process automation, learning from data, producing and using business models, data integration, data quality assessment and cleaning, use of contextual data, etc. Also offered at the undergraduate level, with different requirements, as COMP 4111, for which additional credit is precluded.

COMP 5112 [0.5 credit] (CSI 5154)**Algorithms for Data Science**

Algorithmic techniques to handle (massive/big) data arising from, for example, social media, mobile devices, sensors financial transactions. Algorithmic techniques may include locality-sensitive hashing, dimensionality reduction, streaming, clustering, VC-dimensions, external memory, core sets, link analysis and recommendation systems.

COMP 5113 [0.5 credit] (CSI 5350)**Machine Learning for Healthcare**

Principles, techniques, technology and applications of machine learning for medical data such as medical imaging data, genomic data, physiological signals, speech and language.

COMP 5114 [0.5 credit] (CSI 5351)**Quantum Communications and Networking**

Quantum communications and networking; the use of individual photons and teleportation to represent and transmit information. Theoretical (mathematical) principles. Practical aspects (implementation and software simulation) of quantum communications and networking.

COMP 5115 [0.5 credit] (CSI 5344)**Geometry Processing**

Concepts, representations, and algorithms for processing 3D geometric datasets. Topics include shape representations (e.g., triangle meshes and implicit functions), and the geometry processing pipeline covering the acquisition (e.g., with laser scanning or depth cameras), reconstruction, manipulation, editing, analysis, and fabrication (3D printing) of geometric models.

COMP 5116 [0.5 credit] (CSI 5155)**Machine Learning**

Broad introduction to the fundamental concepts, techniques and algorithms in machine learning. Many of these concepts use probability, statistics, linear algebra and calculus; since some of the algorithms are implemented, programming skills at a level sufficient to write a reasonable non-trivial computer program are desirable.

COMP 5117 [0.5 credit] (CSI 5346)**Mining Software Repositories**

Introduction to the methods and techniques of mining software engineering data. Software repositories and their associated data. Data extraction and mining. Data analysis and interpretation (statistics, metrics, machine learning). Empirical case studies.

COMP 5118 [0.5 credit] (CSI 5347)**Trends in Big Data Management**

In-depth study of recent research articles in the field of data management, with focus on data integration, Internet of Things, large scale data management, recommendation systems, text processing, and question answering. Students will work on a term-long project.

COMP 5119 [0.5 credit] (CSI 5345)**Internet of Things Security**

Security issues related to the Internet of Things (IoT). IoT device software design and device lifecycle, device pairing and configuration, management and security infrastructure, smart home platforms, data and communication protocol security, IoT operating systems, malware, firmware in embedded systems, security administration and best practices.

COMP 5120 [0.5 credit] (CSI 5106)**Cryptography**

Security in encryption algorithms. Encryption and decryption. Entropy, equivocation, and unicity distance. Cryptanalysis and computational complexity. Substitution, transposition, and product ciphers. Symmetric ciphers: block and stream modes. Modular arithmetic. Public key cryptosystems. Factorization methods. Elliptic curve, lattice-based, and homomorphic cryptography. Proofs of security.

COMP 5137 [0.5 credit] (CSI 5187)**Applications of NLP and ML in Software Engineering**

Qualitative Coding of Software Engineering Artifacts, Case Study Research, Natural Language Processing Pipelines and Lexicons, Text Similarity Measures, Information Extraction and Classification, Clustering, Supervised Machine Learning, Quantitative Evaluation of NLP and ML Techniques, Deep Learning, Word Embeddings, Transformers.

COMP 5138 [0.5 credit] (CSI 5186)**AI-enabled Software Verification and Testing**

Automated decision procedures, SAT/SMT solvers; symbolic execution, random and local search algorithms; evolutionary and genetic programming; multi-objective and bio-inspired optimization, search-based software engineering; machine learning for software engineering; and software testing case studies for cyber-physical, deep learning, autonomous driving, and network systems.

COMP 5139 [0.5 credit] (CSI 5177)**Advanced Machine Learning**

Advanced topics in machine learning such as deep learning including CNNs, RNNs, GANs, Diffusion models, Transformers, Deep clustering, transfer learning, domain adaptation, few-shot learning, zero-shot learning, self-supervised learning and Interpretability of ML methods.

COMP 5201 [0.5 credit] (CSI 5147)**Computer Animation**

Theories and techniques in 3D modeling and animation. Animation principles, categories, and history. Forward and inverse kinematics. Motion capture, editing and retargeting. Flexible bodies. Particle animation. Behavioral animation. Human modeling. Facial animation. Cloth animation and other sub-topics.

COMP 5202 [0.5 credit] (CSI 5146)**Computer Graphics**

Principles and advanced techniques in rendering and modelling. Research field overview. Splines, subdivision surfaces and hierarchical surface representations. Physics of light transport, rendering equation and Bidirectional Reflectance Distribution Function. Classical ray tracing, radiosity, global illumination and modern hybrid methods. Plenoptic function and image-based rendering.

COMP 5203 [0.5 credit] (CSI 5173)**Data Networks**

Mathematical and practical aspects of design and analysis of communication networks. Topics include: basic concepts, layering, delay models, multi-access communication, queuing theory, routing, fault-tolerance, and advanced topics on high-speed networks, ATM, mobile wireless networks, and optical networks.

COMP 5204 [0.5 credit] (CSI 5124)
Computational Aspects of Geographic Information Systems

Through recent advances in navigation systems, mobile devices, and new software such as Mapquest and Google Earth, GIS is becoming increasingly important and exciting from a CS perspective. This course lays the algorithmic foundations to understand, use and further this technology.

Also offered at the undergraduate level, with different requirements, as COMP 4202, for which additional credit is precluded.

COMP 5205 [0.5 credit] (CSI 5151)
Virtual Environments

Basic concepts. Virtual worlds. Hardware and software support. World modeling. Geometric modeling. Light modeling. Kinematic and dynamic models. Other physical modeling modalities. Multi-sensor data fusion. Anthropomorphic avatars. Animation: modeling languages, scripts, real-time computer architectures. Virtual environment interfaces. Case studies.

COMP 5206 [0.5 credit] (CSI 5183)
Evolutionary Computation and Artificial Life

Study of algorithms based upon biological theories of evolution, applications to machine learning and optimization problems. Possible topics: Genetic Algorithms, Classifier Systems, and Genetic Programming. Recent work in the fields of Artificial Life (swarm intelligence, distributed agents, behavior-based AI) and of connectionism.

Precludes additional credit for COMP 4107.

COMP 5207 [0.5 credit] (CSI 5112)
Software Engineering

Topics of current interest in Software Engineering, such as requirements engineering, precise and advanced modelling, development processes, change management, standards, and emerging types of applications.

COMP 5209 [0.5 credit] (CSI 5135)
Visual Analytics

Principles, techniques, technology and applications of information visualization for data analysis. Topics include human visual perception, cognitive processes, static and dynamic models of image semantics, interaction paradigms, big data visual analysis case studies.

Includes: Experiential Learning Activity

COMP 5210 [0.5 credit] (CSI 5167)
Human-Computer Interaction Models, Theories, and Frameworks

Emphasis on the application of theory to user interface design. Review of main theories of human behaviour relevant to HCI, including especially cognitive dimensions of notations framework, mental models, distributed cognition, and activity theory, and their application to design and development of interactive systems.

Lecture

COMP 5218 [0.5 credit] (CSI 5218)
Uncertainty Evaluation in Engineering Measurements and Machine Learning

Uncertainty, uncertainty propagation, Bayesian inference, sensor fusion, time series, Gaussian processes, integrating scientific/user knowledge into machine learning, neural networks for differential equations, probabilistic deep learning, sequential decision making. Case studies will be drawn from various fields including biomedical, autonomous vehicles, sensors, and signal processing.

COMP 5220 [0.5 credit] (CSI 5175)
Mobile Commerce Technologies

Wireless networks support for m-commerce; m-commerce architectures and applications; mobile payment support systems; business models; mobile devices and their operating systems; mobile content presentation; security issues and solutions; relevant cross layer standards and protocols; case studies.

Includes: Experiential Learning Activity

COMP 5301 [0.5 credit] (CSI 5122)
Software Usability

Design principles and metrics for usability. Qualitative and quantitative methods for evaluation of software system usability: Heuristic evaluation, usability testing, usability inspections and walkthroughs, cognitive walkthroughs, formal usability experimentation. Ethical concerns. Economics of usability. Integration of usability engineering lifestyle.

COMP 5302 [0.5 credit] (CSI 5118)
Automated Verification & Validation of Software

Topics in formal test derivation methods, test management, high-level, CASE-based verification and validation, data-flow and control-flow measures and metrics for assessing quality of designs and code, regression analysis and testing.

COMP 5304 [0.5 credit] (CSI 5169)**Wireless Networks and Mobile Computing**

Computational aspects and applications of design and analysis of mobile and wireless networking. Topics include Physical, Link Layer, Media Access Control, Wireless, Mobile LANs, Ad-Hoc, Sensor Networks, Power Consumption optimization, Routing, Searching, Service Discovery, Clustering, Multicasting, Localization, Mobile IP/TCP, File Systems, Mobility Models, Wireless Apps.

COMP 5305 [0.5 credit] (CSI 5129)**Advanced Database Systems**

In-depth study on developments in database systems shaping the future of information systems, including complex object, object-oriented, object-relational, and semi-structured databases. Data structures, query languages, implementation and applications.

COMP 5306 [0.5 credit] (CSI 5100)**Data Integration**

Materialized and virtual approaches to integration of heterogeneous and independent data sources. Emphasis on data models, architectures, logic-based techniques for query processing, metadata and consistency management, the role of XML and ontologies in data integration; connections to schema mapping, data exchange, and P2P systems.

COMP 5307 [0.5 credit] (CSI 5101)**Knowledge Representation**

KR is concerned with representing knowledge and using it in computers. Emphasis on logic-based languages for KR, and automated reasoning techniques and systems; important applications of this traditional area of AI to ontologies and semantic web.

COMP 5308 [0.5 credit] (CSI 5102)**Topics in Medical Computing**

Introductory course on data structures, algorithms, techniques, and software development related to medical computing (in particular spatial modeling). Topics may include: computational geometry algorithms for cancer treatment, medical imaging, spatial data compression algorithms, dynamic programming for DNA analysis.

COMP 5309 [0.5 credit] (CSI 5168)**Digital Watermarking**

Overview of recent advances in watermarking of image, video, audio, and other media. Spatial, spectral, and temporal watermarking algorithms. Perceptual models. Use of cryptography in steganography and watermarking. Content authentication, copy control, intellectual property, digital rights management and other applications.

COMP 5310 [0.5 credit] (CSI 5152)**Evolving Information Networks**

Convergence of social and technological networks with WWW. Interplay between information content, entities creating it and technologies supporting it. Structure and analysis of such networks, models abstracting their properties, link analysis, search, mechanism design, power laws, cascading, clustering and connections with work in social sciences.

Also offered at the undergraduate level, with different requirements, as COMP 4206, for which additional credit is precluded.

COMP 5340 [0.5 credit] (CSI 5340)**Introduction to Deep Learning and Reinforcement Learning**

Fundamentals of machine learning; multi-layer perceptron, universal approximation theorem, back-propagation; convolutional networks, recurrent neural networks, variational auto-encoder, generative adversarial networks; components and techniques in deep learning; Markov Decision Process; Bellman equation, policy iteration, value iteration, Monte-Carlo learning, temporal difference methods, Q learning, SARSA, applications.

COMP 5341 [0.5 credit] (CSI 5341)**Learning-based Computer Vision**

Introduction to learning-based computer vision; statistical learning background; image processing and filtering primer; convolutional neural networks (CNNs), network layers, computer vision data sets and competitions; computer vision problems, in particular, image classification, detection and recognition, semantic segmentation, image generation, multi view problems and tracking.

COMP 5342 [0.5 credit] (CSI 5342)**Ubiquitous Sensing for Smart Cities**

Sensor and actuator networks. Dedicated and non-dedicated sensing. Vehicular sensing and smart transportation. Software Defined Things. Sensing as a service. Machine and deep learning-based misbehaviour detection. IoT-data analytics ecosystems. Federated Learning. AI-based security solutions. Auction and game theory concepts in ubiquitous sensing.

COMP 5343 [0.5 credit] (CSI 5343)**AI-Enabled Communications**

Wireless networking fundamentals. Device to-device communications. Networking with cognitive radio. Cyber physical systems (CPS). Self-organization. Supervised and unsupervised learning. Reinforcement learning. Deep learning.

COMP 5388 [0.5 credit] (CSI 5388)**AI for Cybersecurity Applications**

Cybersecurity problems and challenges. Supervised and unsupervised learning. Classification and regression algorithms. Performance assessment in cybersecurity domains. Techniques for imbalanced domains. Anomaly detection. Active learning strategies. Cybersecurity of data streams. ML vulnerability. NLP for cybersecurity. Malware, intrusion, credit card fraud detection, phishing, authentication abuse prevention.

Prerequisite(s): There are no official prerequisites for this course. However, students should have reasonable exposure to Artificial Intelligence, Machine Learning, and some programming experience in a high-level language.

COMP 5401 [0.5 credit] (CSI 5389)**Electronic Commerce Technologies**

Introduction to business models and technologies. Search engines. Cryptography. Web services and agents. Secure electronic transactions. Value added e-commerce technologies. Advanced research questions.

COMP 5402 [0.5 credit] (CSI 5142)**Protocols for Mobile and Wireless Networks**

Link and network layer protocols of wireless networks; applications of wireless networks may be discussed. Topics may include: protocol implementation, mobile IP, resource discovery, wireless LANs/PANs, and Spread spectrum.

Precludes additional credit for SYSC 5306.

COMP 5405 [0.5 credit] (CSI 5380)**Systems and Architectures for Electronic Commerce**

E-commerce system architecture with a focus design patterns. Web servers and application frameworks. Web protocols, services, and client technologies. Scalability through load balancing, clustering, and code optimization. Internationalization, accessibility, and privacy. Data mining and sharing approaches for digital targeted advertising. E-commerce development project.

COMP 5406 [0.5 credit] (CSI 5105)**Network Security and Cryptography**

Advanced methodologies selected from symmetric and public key cryptography, network security protocols and infrastructure, identification, anonymity, privacy technologies, secret-sharing, intrusion detection, firewalls, access control technologies, and defending network attacks.

COMP 5407 [0.5 credit] (CSI 5116)**Authentication and Software Security**

Specialized topics in security including advanced authentication techniques, user interface aspects, electronic and digital signatures, security infrastructures and protocols, software vulnerabilities affecting security, untrusted software and hosts, protecting software and digital content.

COMP 5408 [0.5 credit] (CSI 5121)**Advanced Data Structures**

Simple methods of data structure design and analysis that lead to efficient data structures for several problems. Topics include randomized binary search trees, persistence, fractional cascading, self-adjusting data structures, van Emde Boas trees, tries, randomized heaps, and lowest common ancestor queries.

COMP 5409 [0.5 credit] (CSI 5127)**Applied Computational Geometry**

Computer-based representation and manipulation of geometric objects. Design and analysis of efficient algorithms for solving geometric problems in applied fields such as Computer-Aided Design and Manufacturing, Cartography, Materials Science, and Geometric Network Design.

COMP 5500 [0.5 credit] (CSI 5352)**Internet Measurements and Security**

Measurement methodologies for understanding complex Internet phenomena and behaviors including: spread of vulnerabilities, remote network topologies, attack patterns, content popularity, Internet censorship, service quality, and adoption of security systems. Tools for efficient measurements, large-scale data analysis, stats, reproducibility of results. Ethical considerations.

COMP 5501 [0.5 credit] (CSI 5111)**Software Quality Engineering**

Software quality issues. Quality components and metrics. Software process quality. Software reliability engineering. Software design for testability. Requirements capture and validation. Systematic design validation; grey-box approach, test design, implementation and management, case studies in validation and verification of communications software. Object-oriented design and test.

COMP 5503 [0.5 credit] (CSI 5115)**Database Analysis & Design**

The dimensional and multidimensional data models for data warehousing. Data dependencies and decomposition. Structure and use of data definition and manipulation languages. Database economics, engineering, deployment and evolution. Issues in integrity, security, the Internet and distributed databases. Relationships to decision support systems.

COMP 5505 [0.5 credit] (CSI 5386)**Natural Language Processing**

Overview of both rule-based or symbolic methods and statistical methods as approaches to Natural Language Processing (NLP), with more emphasis on the statistical ones. Applications such as information retrieval, text categorization, clustering, and statistical machine translation could be discussed.

COMP 5604 [0.5 credit] (CSI 5174)**Validation Methods for Distributed Systems**

Review of formal specification and description techniques for distributed and open systems. Verification techniques. Correctness proofs. Verification of general properties of distributed systems. Analysis and relief strategies. Testing techniques. Test generation strategies. Test architectures.

COMP 5606 [0.5 credit] (CSI 5161)**Principles of Distributed Simulation**

Distributed simulation principles and practices. Synchronization protocols: Optimistic vs Conservative, Deadlock detection in conservative simulations, Time warp simulation. Distributed interactive simulation: Data distribution management, Interest management, High Level Architectures (HLA), Run Time Infrastructure (RTI). Distributed web-based and agent based simulation. Real time applications.

COMP 5700 [0.5 credit] (CSI 5108)**Introduction to Convex Optimization**

Linear, nonlinear and convex problems. Convex affine sets. Convex, quasiconvex and log-convex functions. Operations preserving convexity. Recognizing and formulating convex optimization problems. The Lagrange function, optimality conditions, duality, geometric and saddle-point interpretations. Least-norm, regularized and robust approximations. Statistical estimation, detector design. Adaptive antennas.

COMP 5701 [0.5 credit] (CSI 5107)**Principle of Intelligent Transportation Systems**

Fundamental concepts of ITS. Computer information and communication for ITS. The backbone of ITS communication, network topologies and configurations. ITS models and evaluation Methods. Advanced transportation management, advanced traveler information and advanced driver assistant systems. Smart mobility and GPS localization algorithms.

COMP 5703 [0.5 credit] (CSI 5163)**Algorithm Analysis and Design**

Topics of current interest in the analysis and design of sequential and parallel algorithms for non-numerical, algebraic and graph computations. Lower bounds on efficiency of algorithms. Complexity classes.

COMP 5704 [0.5 credit] (CSI 5131)**Parallel Algorithms and Applications in Data Science**

Multiprocessor architectures from an application programmer's perspective: programming models, processor clusters, multi-core processors, GPU's, algorithmic paradigms, efficient parallel problem solving, scalability and portability. Projects on high performance computing in Data Science, incl. data analytics, bioinformatics, simulations. Programming experience on parallel processing equipment. Includes: Experiential Learning Activity

COMP 5706 [0.5 credit] (CSI 5387)**Data Mining & Concept Learning**

Concepts and techniques of data mining. Methods for data summarization and data preprocessing. Algorithms for finding frequent patterns and association analysis; classification; cluster analysis and anomaly detection. Model selection, model evaluation and statistical significance testing. Applications of data mining and coping with Big Data.

COMP 5707 [0.5 credit] (CSI 5110)**Principles of Formal Software Development**

Methodologies in formal software specification, development, and verification. The use of theorem proving, automated deduction, and other related formal methods for software correctness. Applications in program verification and secure computation.

COMP 5709 [0.5 credit] (CSI 5165)**Combinatorial Algorithms**

Design of algorithms for solving problems that are combinatorial in nature, involving exhaustive generation, enumeration, search and optimization. Algorithms for generating basic combinatorial objects and for solving hard optimization problems. Metaheuristic search, backtracking, branch-and-bound. Computing isomorphism of combinatorial objects.

COMP 5801 [0.5 credit] (CSI 5388)**Topics in Machine Learning****COMP 5805 [0.5 credit] (CSI 5166)****Applications of Combinatorial Optimization**

Topics in combinatorial optimization with emphasis on applications in Computer Science. Topics include network flows, various routing algorithms, polyhedral combinatorics, and the cutting plane method.

COMP 5808 [0.5 credit] (CSI 5188)**Trusted Computing and Emerging Attacks**

A systematic discussion of current threats to code execution and the paradigm of employing hardware to achieve secure code execution. Topics include state-of-the-art security hardware support including trusted execution environments on various platforms/architectures, and applications of such hardware support to address various attack vectors.

COMP 5900 [0.5 credit] (CSI 5140)**Special Topics in Computer Science**

Special topics not covered by other graduate courses. Details will be available from the School at the time of registration.

COMP 5901 [0.5 credit] (CSI 5901)**Directed Studies (M.C.S.)**

A course of independent study under the supervision of a member of the School of Computer Science.

COMP 5903 [1.0 credit] (CSI 6900)**Graduate Project (M.C.S.)**

A one- or two-session course. For M.C.S. non-thesis option students only.

COMP 5905 [2.5 credits] (THM 7999)**M.C.S. Thesis****COMP 5913 [0.0 credit] (CGI 6001/CGI 6002)****Master's Co-operative Work Term****COMP 6100 [0.5 credit] (CSI 7131)****Advanced Parallel and Systolic Algorithms**

Continuation of COMP 5704.

COMP 6104 [0.5 credit] (CSI 7314)**Advanced Topics in Object-Oriented Systems**

Advanced object-oriented software engineering, in particular the issues of reuse and testing. Sample topics include: interaction modeling; class and cluster testing; traceability; design patterns and testing; the C++ standard template library. Students will carry out research.

COMP 6601 [0.5 credit] (CSI 7160)**Advanced Topics in the Theory of Computing****COMP 6602 [0.5 credit] (CSI 7170)****Advanced Topics in Distributed Computing****COMP 6603 [0.5 credit] (CSI 7161, CSI 7561)****Advanced Topics in Programming Systems and Languages****COMP 6604 [0.5 credit] (CSI 7162)****Advanced Topics in Computer Applications****COMP 6605 [0.5 credit] (CSI 7163)****Advanced Topics in Computer Systems****COMP 6901 [0.5 credit] (CSI 7901)****Directed Studies (Ph.D.)****COMP 6902 [0.5 credit] (CSI 7900)****Graduate Project (Ph.D.)****COMP 6907 [0.0 credit] (CSI 9998)****Doctoral Comprehensive**

Committee assembled approves at least 3 topics for written examination: typically, a major and two minor areas. An oral examination occurs if the written exam is passed. Both elements must take place within the first 4 terms following initial registration in the program. The comprehensive may be failed, passed conditionally (i.e., with extra course requirements) or passed unconditionally. If failed this course may be retaken at most one time.

COMP 6908 [0.0 credit] (CSI 9997)**Doctoral Proposal**

Within 8 terms following initial registration in the program, a document generally defining the problem addressed, relating it to the literature, and outlining the hypotheses, goals, research methodology, initial results and validation approach must be submitted to an examination committee and successfully defended.

COMP 6909 [0.0 credit] (CSI 9999)**Ph.D. Thesis**