# (GWC)$^2$ Chemistry – Quantum Information M.Sc./Ph.D. Collaborative Program

***Quantum Information MSc/PhD Collaborative Program***

The University of Waterloo, home of the Institute for Quantum Computing, offers graduate students unique opportunities to learn about and engage in world-leading research in quantum information through a wide range of advanced research projects and advanced courses on the foundations, applications and implementation of quantum information processing.

In particular, the University of Waterloo offers a unique interdisciplinary graduate program in Quantum Information that leads to MMath, MSc, MASc, and PhD degrees. This program is a collaboration between the Institute for Quantum Computing and:

- The Departments of Applied Mathematics, Combinatorics and Optimization, and the David R. Cheriton School of Computer Science in the Faculty of Mathematics
- The Departments of Chemistry and Physics and Astronomy in the Faculty of Science
- The Department of Electrical and Computer Engineering in the Faculty of Engineering.

These academic units are referred to hereinafter as the home units.

MMath, MSc, and MASc students will receive both strong and broad foundations in quantum information science, coupled with knowledge and expertise obtained within their home programs. This will prepare them for the workforce and/or further graduate studies and research leading towards a PhD degree.

PhD students will be especially well-prepared for careers as scholars and researchers, with advanced expertise in quantum information science, together with the focus of their home programs. This new program is designed to provide students with knowledge of quantum information, including both theory and its implementations, advanced expertise in quantum information science and in home program disciplines, as well as training in research.

Admission requirements are the same as those of the home programs. The home unit in which an applicant intends to pursue graduate study must approve the application. Interested students should apply directly to one of the following units via the regular university application process:

Department of Applied Mathematics
Department of Chemistry
Department of Combinatorics and Optimization
David R. Cheriton School of Computer Science
Department of Electrical and Computer Engineering
Department of Physics and Astronomy

***M.Sc. Program***

**Admission Requirements**

M.Sc. students in the collaborative program in quantum information must meet the M.Sc. admission requirements of the participating department in which they are enrolled. The minimum academic requirement for admission to the (GWC)$^2$ M.Sc. program is an honours bachelor's degree (or its equivalent) in Science from a recognized university with a second-class (B) standing. Strong emphasis is also placed on the letters of recommendation received in support of the student's application. Students from foreign countries where English is not the language of instruction are also required to prove their proficiency in English.

**Degree Requirements**

(GWC)$^2$ M.Sc. students must successfully complete at least four one-term graduate courses one of which is Chemistry 794(0) (M.Sc. Seminar), and submit and defend an acceptable thesis (topic and advisor approved the QI Committee). M.Sc. students in the collaborative program in quantum information must complete a minimum of 1.5 graduate credits, which must include the following quantum information

courses; **QIC 710 – Quantum Information Processing, QIC 750 – Implementation of Quantum Information Processing** and one of Chem 745 (Stat Mech), 746 (Quant. Chem), 756 (Spectroscopy), 769 (Phys. Org. Chem.), 713 (Chem. of Inorg. Sol. Mats.).

***Ph.D. Program***

**Admission Requirements**

Ph.D. students in the collaborative program in quantum information must meet the Ph.D. admission requirements of the participating department in which they are enrolled. The minimum academic requirements for the (GWC)$^2$ normally consists of a Master's degree in Science from a recognized university with a second-class (B) standing. Strong emphasis is also placed on the letters of recommendation received in support of the student's application. Students from foreign countries where English is not the language of instruction are also required to prove their proficiency in English.

**Degree Requirements**

Students entering the PhD program following completion of a Master's degree equivalent to that offered by one of the participating academic units at the University of Waterloo must either previously have successfully completed two core quantum information courses, QIC 710 (Quantum Information Processing) and QIC 750 (Implementation of Quantum Information Processing), or their equivalents at another institution, or must complete them in addition to a minimum of two one-term courses (all courses of weight 0.5 unit).

Completion of two graduate courses in quantum information (other than QIC 710 and QIC 750) is required as part of the requirement for a PhD in quantum information at the University of Waterloo. Note in this context that any QIC course offered by the Department of Chemistry satisfies one of the Chemistry course requirements.

Chemistry requires the equivalent of two (2) 0.5 credit Chemistry Graduate courses, which may be satisfied by QIC courses offered by the Department of Chemistry. Where a student does not take a QIC course offered by the Department of Chemistry, another Graduate Chemistry course(s) must be taken to meet the Chemistry course requirement.

***Seminar Milestones***

PhD students in the Quantum Information program must successfully complete a seminar milestone consisting of one seminar held at the Institute for Quantum Computing (IQC) (completed by the 9$^{th}$ Term of the Ph.D. program), and one seminar on a QI topic aimed at members of the home academic unit.

Students must also fulfill the Chemistry program PhD Seminar Proposal milestone. This can be fulfilled simultaneously with the QI requirement for one seminar on a QI topic aimed at members of the home unit.

***Ph.D. Direct from B.Sc or M.Sc. Program***

*Direct Entry from B.Sc*: This option is possible for outstanding students who graduated with an overall 'A' standing at the undergraduate level.

*Direct Transfers To Ph.D. From M.Sc.* Exceptional students may transfer directly into the Ph.D. program without first completing all of the M.Sc. requirements. The following guidelines will be applied in consideration of applications for such a transfer.

- ✓ The applicant who is applying for direct transfer must have demonstrated a superior academic record both at the undergraduate and graduate level. This will normally mean that the student has a minimum overall B+ average as an undergraduate and has demonstrated a first-class standing with consistently above average performance in at least two graduate courses as well as in the Masters Seminar.
- ✓ The applicant must have already demonstrated an oral and written communication ability appropriate for a Ph.D. level student. In addition, there must be clear evidence of research productivity and promise.
- ✓ The request will be considered by the Director/Coordinating Committee at the end of the student's third term in the M.Sc. program. If the result is positive, the Director will forward this recommendation and supporting documentation to the Dean of Graduate Studies.

***Degree Requirements***

Students in the Ph.D. Direct Programs must complete:

- QIC 710 and QIC 750
- one of Chem 745 (Statistical Mechanics), 746 (Quantum Chemistry), 756 (Spectroscopy), 769 (Physical Organic Chemistry), 713 (Chemistry of Inorganic Solid Materials),
- two additional QIC courses,
- the MSc thesis seminar proposal milestone,
- the PhD thesis seminar proposal milestone,
- Institute for Quantum Computing (IQC) seminar milestone,
- a PhD comprehensive oral examination milestone, and
- an original research dissertation in Quantum Information

Chemistry requires the equivalent of two (2) 0.5 credit Chemistry Graduate courses, which may be satisfied by QIC courses offered by the Department of Chemistry. Where a student does not take a QIC course offered by the Department of Chemistry, another Graduate Chemistry course(s) must be taken to meet the Chemistry course requirement. Any QIC course offered by the Department of Chemistry satisfies one of the Chemistry course requirements.

***Required Quantum Information Core Course Descriptions***

**Core Courses**

Students in all three faculties will be required to take two core quantum information courses (and must also meet the course requirements of their home program). These interdisciplinary courses provide a strong foundation in quantum information science.

**QIC710 Quantum Information Processing (0.5)**

Review of basics of quantum information and computational complexity; Simple quantum algorithms; Quantum Fourier transform and Shor factoring algorithm: Amplitude amplification, Grover search algorithm and its optimality; Completely positive trace-preserving maps and Kraus representation; Non-locality and communication complexity; Physical realizations of quantum computation: requirements and examples; Quantum error-correction, including CSS codes, and elements of fault-tolerant computation; Quantum cryptography; Security proofs of quantum key distribution protocols; Quantum proof systems. Familiarity with theoretical computer science or quantum mechanics will also be an asset, though most students will not be familiar with both.

**QIC750 Implementation of Quantum Information Processing (0.5)**
Photonic quantum computing (interference and superposition principle of light, polarization; photoelectric effect; photons ; dual rail qubits; beamsplitters and phase rotators; the Knill-Laflamme-Milburn proposal), Ion Trap quantum computing (trapping ions, optical pumping, Rabi oscillations, Raman pulses, shelving readout, motional gates), Atomic quantum computing (light-induced forces, optical lattices, Feshbach resonances), Nuclear Magnetic Resonance (single spin in a magnetic field; states at high temperatures; Rabi oscillations, interactions between spins; frequency-addressing), Electron Spin Resonance (basics of microwave control, ESR in the solid state), Superconducting qubits ( a single wavefunction for a macroscopic number of particles / London theory of superconductors; the Josephson effect; quantizing electric circuits; different types of superconducting qubits; decoherence sources).

***PhD Program Quantum Information Specialization Courses***

PhD students are also required to take two additional courses in quantum information. PhD students who take a Quantum information course that is cross-listed with graduate Chemistry courses meet the one half credit graduate level elective Chemistry course requirements.

- QIC880 Nanoelectronics for Quantum Information Processing
- QC890 Topics in Quantum Information
- QC895 Topics in Quantum Information

**GUELPH-WATERLOO CENTRE FOR GRADUATE WORK IN CHEMISTRY AND BIOCHEMISTRY**

**$(GWC)^2$ Website: http://www.gwc2.on.ca**

***Contacts for the Quantum Information Program***

*$(GWC)^2$ :* Email: gwc@uoguelph.ca Website: http://www.gwc2.on.ca

*Quantum Information Graduate Program: http://new.iqc.ca/welcome/graduate-studies*

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*Quantum Information Interdepartmental Group – Chemistry Members*

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***Application Information***

Application is made through the on-line Ontario University Application Centre (OUAC) through the University of Waterloo:

http://horizon.ouac.on.ca/webapp/account.d2w/report?ident=ACCOUNT_DSP&merchant_rn=656872&action_id=choose